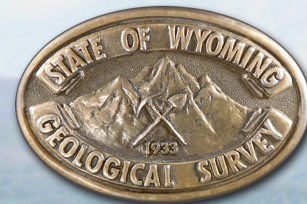# Wyoming State Geological Survey

Thomas A. Drean, Director and State Geologist

Bear River Basin Water Plan Update Groundwater Study Level I (2010 – 2014)

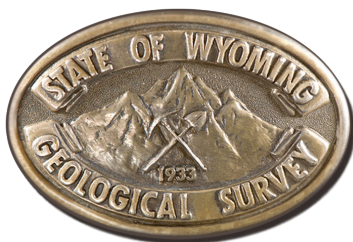# Available Groundwater Determination Technical Memorandum No. 6

by

Karl G. Taboga, Timothy T. Bartos, Paul Taucher, Laura L. Hallberg, Melanie L. Clark, James Stafford, Tomas Gracias and Seth J. Wittke

Mary Kate McCarney, Editor

Prepared for the Wyoming Water Development Commission

Laramie, Wyoming
2014

Director and State Geologist Thomas A. Drean

Bear River Basin Water Plan Update
Groundwater Study
Level I (2010 – 2014)

Available Groundwater Determination
Technical Memorandum No. 6

Prepared for the Wyoming Water Development Commission

This publication is also available online at:
www.wsgs.uwyo.edu/Research/Water-Resources/BRB/

Wyoming State Geological Survey

Cover: Bear River above Evanston, Wyoming. Photo by Antony R. Bergantino (2009).

Bear River Basin Water Plan Update
Groundwater Study
Level I (2010 – 2014)

Available Groundwater Determination
Technical Memorandum No. 6

March 2014

Paul Taucher,[3] Timothy T. Bartos,[2] Karl G. Taboga, Laura L. Hallberg,[2] Melanie L. Clark,[2] James Stafford,[1] Tomas Gracias,[1] and Seth J. Wittke[1]

Mary Kate McCarney, Editor

This report was prepared under contract for the Wyoming Water Development Commission (WWDC) by the Wyoming State Geological Survey (WSGS)[1], the United States Geological Survey (USGS)[2], and the Water Resources Data System (WRDS) in cooperation with the Wyoming State Engineer's Office (WSEO) and the Wyoming Oil and Gas Commission (WOGCC).

[1]Wyoming State Geologic Survey, P.O. Box 1347, Laramie, Wyoming, 82073-1347
[2]U.S. Geological Survey, Wyoming Water Science Center, 21 Progress Circle, Suite 6, Cheyenne, Wyoming, 82007
[3]Energy Compliance LLC, 2302 Nighthawk Drive, Laramie, Wyoming, 82070

Figures

Tables

LIST OF PLATES
(Paper and/or DVD copies contained in back cover pocket)

x

Chapter 1
Introduction

Paul Taucher and Karl Taboga

The Wyoming State Engineer's Office (SEO) published the first State Framework Water Plan in 1973 under the Wyoming Water Planning Program. The publication presented a water resources plan for the entire state of Wyoming and included summary water plans for each of the state's seven major river drainages. In 1975, the Wyoming Legislature established the Wyoming Water Development Commission (WWDC) and Wyoming Water Development Office (WWDO) to coordinate planning, development and project management efforts for the state's water and related land resources. Between 1979 and 1995, the WWDO completed several, major river basin planning studies.

The development of the present State Water Planning Process began in 1997 when the state legislature directed WWDC to conduct a feasibility study in collaboration with the University of Wyoming (UW), the Water Resources Data System (WRDS) and the SEO that included public input and compilation of a statewide water inventory. Based on the feasibility study, the Legislature accepted the recommended planning framework and funded the Statewide Water Planning Process in 1999 to update the original 1973 State Framework Water Plan, and specifically to:

- Inventory the state's water resources and related lands.
- Summarize the state's present water uses and project future water needs.
- Identify alternatives to meet projected future water needs.
- Provide water resource planning direction to the state of Wyoming for a 30-year time-frame.
- The Wyoming Framework Water Plan (WWC Engineering and others, 2007), compiled between 2001 and 2006, summarized the separate water plans for Wyoming's seven major river basins (**Fig. 1-1**).

The technical memoranda of the existing Bear River Basin water plans (Forsgren and Associates, 2001; Wyoming Water Development Office (WWDO), 2012) contain ground water resource

investigations that thoroughly examine the basin's groundwater resources and their use. This memorandum represents the most current assessment of the groundwater resources in the Bear River Basin; it updates and expands the information presented in the previous groundwater investigations. The data contained in this memorandum are a compilation of existing information obtained by several state and federal agencies. While original maps and tables were developed, and existing maps and tables were updated and modified, no original research was conducted for this memorandum.

The format of this update follows the general layout of other, recent groundwater determination updates co-authored by the Wyoming State Geological Survey (WSGS) and U.S. Geological Survey (USGS) for the Wind/Bighorn River Basin (2012), the Green River Basin (2010), and the Platte River Basin (2013); this memorandum incorporates much of the content of these three, previous studies, frequently without citation.

1.1 Interagency Agreement and scope

The WWDC and WSGS entered into an Interagency Agreement in June 2010 to update the groundwater information contained in the previous Bear River Basin water plans (Forsgren and Associates, 2001; WWDO, 2012). The previous Bear River water plans are available on the WWDC website at http://waterplan.state.wy.us/plan/bear/bear-plan.html. The agreement outlined the following tasks for this update of the Bear River Basin water plans:

- **Identify the major (most widely used) aquifers in the Bear River Basin.** To make this determination, the USGS defined all of the aquifers and confining units in the Bear River Basin and presented the information on hydrostratigraphic nomenclature charts (**Pl. 5**). Based on these detailed analyses, the Geographic Information System (GIS) geologic units mapped on **Plate 1** and described in Appendix A were organized into a comprehensive hydrostratigraphic chart
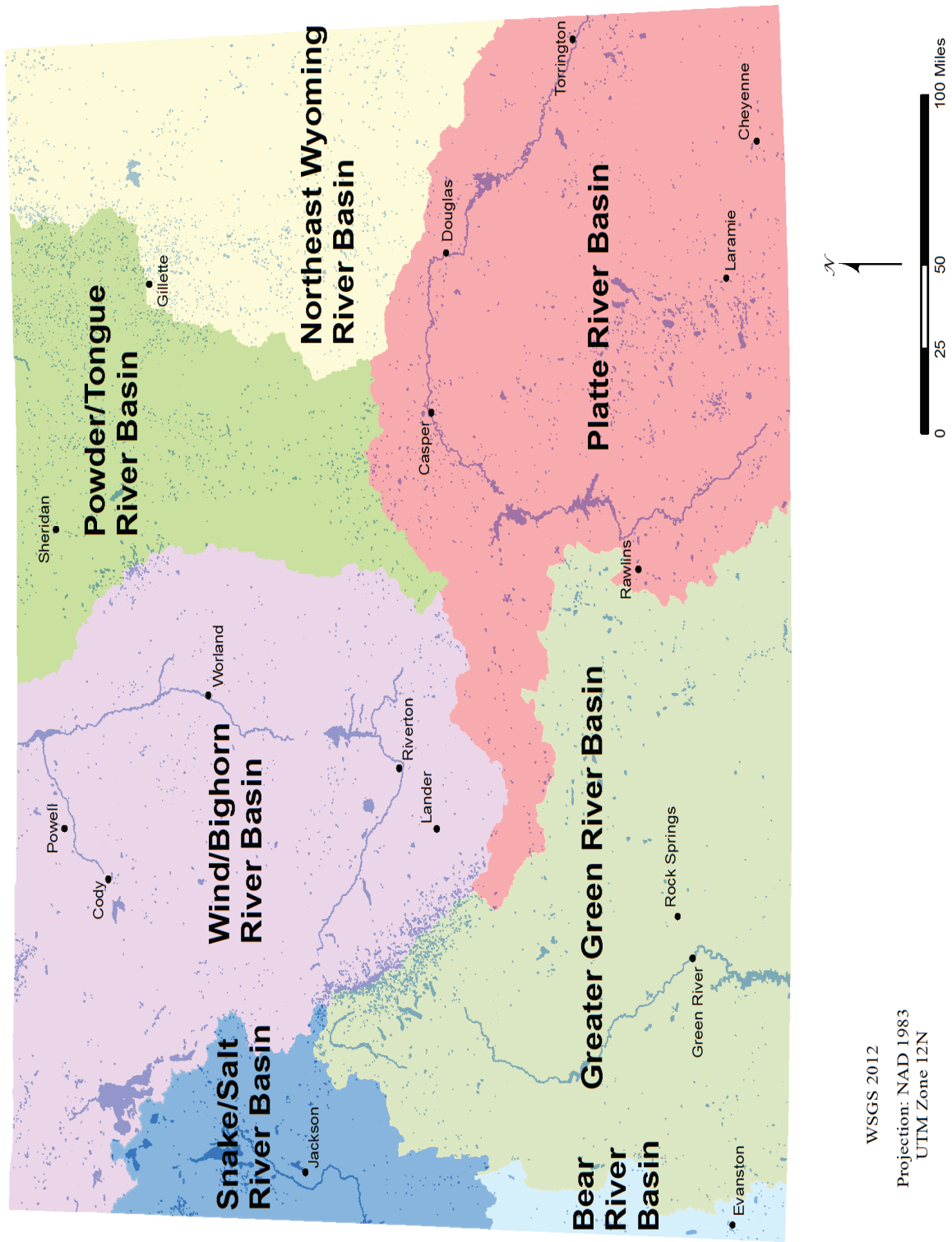
Figure 1-1. Major drainage basins, Wyoming.

Snake/Salt River Basin

Powder/Tongue River Basin

Northeast Wyoming River Basin

Wind/Bighorn River Basin

Platte River Basin

Greater Green River Basin

Bear River Basin

Sheridan

Gillette

Powell

Cody

Worland

Riverton

Lander

Casper

Douglas

Torrington

Rawlins

Cheyenne

Laramie

Rock Springs

Green River

Evanston

Jackson

WSGS 2012

Projection: NAD 1983
UTM Zone 12N

0   25   50   100 Miles

and surface hydrogeology map for the Bear River Basin (**Pl. 2**). In some cases, two or more minor aquifers that are hydrologically connected have been grouped together and treated as a single combined hydrogeologic unit. The general geology of the Bear River Basin is discussed in **Chapter 4**. Individual Bear River Basin aquifers are discussed in detail in **Chapter 7**.

- **Define the three-dimensional extent of the aquifers.**
- **Plate 2** is a map of the outcrop areas for the basin's aquifers and confining units in the Bear River Basin. Five cross sections (**Figs. 4-2** through **4-6**) illustrate the subsurface configuration of the geologic units that constitute the hydrogeologic units at selected areas within the basin. Isopach maps with substantial coverage of the major aquifers in the Bear River Basin are unavailable.
- Describe the following hydraulic, hydrogeologic, and hydrogeochemical properties of the aquifers and confining units:
- Physical characteristics – **Chapters 4** and **7** discuss the lithologic and hydrogeologic characteristics of the hydrogeologic units identified in **Plate 2**.
- Water chemistry with comparisons to applicable state and federal regulatory standards by class of use – **Chapters 5** and **7** contain extensive discussions of basin water quality with comparisons to regulatory standards. Statistical analyses of water chemistry are presented in **Appendices E** and **F**.
- Principal potential pollutants – **Chapter 5** contains a discussion of potential sources of pollution and maps of these facilities are provided in **Figures 5-4** through **5-10**.
- **Estimate the quantity of water in the aquifers.**
- Data sufficient for a basin-wide aquifer-specific assessment of groundwater quantity is not available and is unlikely to ever be developed. The complex geology of most of the Bear River Basin does not lend itself to the general assumptions

about aquifer properties, geometry, and saturated thickness that would be required for a plausible estimate of total and producible groundwater resources. The most important aquifers in the Bear River Basin, that include the Bear River alluvium, Wasatch Formation, Gannett Group, and Nugget Sandstone have been described in numerous specific studies that are more comprehensive and relevant than a summary estimate. Groundwater resource estimates are addressed in this Technical Memorandum by analysis of recharge (**Chapter 6**) and a basin-wide water balance (**Chapter 8**).

- **Describe the aquifer recharge areas.**
- **Plate 2** is a map of the outcrop areas of aquifers and confining units in the Bear River Basin. Maps that depict the outcrop areas used to calculate the annual rate of recharge for specific aquifers and logical groups of aquifers throughout the Bear River Basin are provided in **Figures 6-1** through **6-4.** Recharge is discussed in **Section 5.1** and **Chapter 6**.
- **Estimate aquifer recharge rates.** Existing maps depicting average annual precipitation (**Fig. 3-3**) and estimated recharge rates (**Fig. 5-2**) over the entire Bear River Basin were adapted for presentation in this Technical Memorandum. Existing annual recharge rates were multiplied by aquifer outcrop areas (**Figs. 6-1** through **6-4**) to estimate a range of annual recharge volumes for individual and combined aquifers. The results of these estimates are summarized in **Tables 6-1** through **6-3** and discussed in **Section 6-2**. **Figure 6-5** represents recharge as a percentage of precipitation and **Section 6-2** describes how recharge efficiency varies by individual and combined aquifers overall within the Bear River Basin.
- **Estimate the "safe yield"** potential for the aquifers and describe implications of hydrologically connected groundwater and surface water.

- The concept of "safe yield" is discussed in **Section 5.1.4**. This report provides estimates of total (average annual) recharge for the Bear River Basin in **Chapter 6**, and compares these recharge estimates to current groundwater withdrawals in **Chapter 8**.

- **Describe and evaluate existing groundwater models:**
  Existing groundwater models are identified and evaluated; and recommendations for future groundwater modeling in the Bear River Basin are discussed in **Chapter 7**.

- **Identify future groundwater development opportunities to satisfy projected agricultural, municipal, and industrial demands:**
  Several approaches to address future groundwater development potential are discussed in **Chapter 9**.

  - General and aquifer-specific hydrogeology relative to groundwater development potential is discussed in **Chapters 5** through **7**.

  - **Figures 8-1** through **8-6** show wells permitted in the Bear River Basin by the SEO through February 27, 2012. These Figures include selected groundwater permit statistics and illustrate historic groundwater development patterns. SEO permits issued between January 1, 2001 and February 27, 2012, shown on inset tables contained within these figures, illustrate the focus of recent groundwater development efforts. Existing groundwater development in the Bear River Basin is discussed in **Chapters 7** and **9**.

  - A summary of groundwater development studies and projects in the Bear River Basin, sponsored by the WWDC, is included in Appendix B of this Technical Memorandum. The development potential of specific aquifers based on information compiled from these and

other previous studies is described in **Chapter 7**.

- Groundwater development prospects for the Bear River Basin, identified in the ground water resource investigations of previous Bear River Basin water plans (Forsgren and Associates, 2001; WWDO, 2012) are briefly discussed in **Chapter 9**.

- Current WWDC and SEO projects related to groundwater development in the Bear River Basin are discussed in **Chapter 9**.

1.2 Agency participation

This Technical Memorandum is the result of a cooperative effort by the WWDC/WWDO, WSGS, USGS, and the Water Resources Data System (WRDS). The SEO and the Wyoming Department of Environmental Quality (WDEQ) contributed significant resources for developing some of the data presented in this Technical Memorandum.

- The WWDO and WRDS provided the WSGS with overall program guidance and standards, software, and format requirements for deliverables (maps, databases, metadata, tables, graphs, etc.).

- The WSGS was the primary compiler of the information developed in **Chapters 1, 2, 3, 4, 5, 6, 8,** and **9**.

- The USGS, under contract with the WSGS, compiled the information used in **Chapter 7** and **Section 5.6.1**.

- The WSGS and USGS cooperated on sections of **Chapters 5** and **9**.

- WRDS provided assistance by providing hard copies of the final Technical Memorandum and will feature the associated deliverables on its website at http://www.wrds.uwyo.edu/ on behalf of WWDC/WWDO.

The WWDO, the water development planning agency for Wyoming, administers publicly-funded development, construction, rehabilitation, and related groundwater projects through its

professional, legal, and support staff at the WWDO.

The WSGS is a separate operating agency under the executive branch of state government (Wyoming State Statutes 9-2-801, 9-2-803 through 9-2-810). The WSGS's purposes are 1) to study, examine, and understand the geology, mineral resources, and physical features of the state; 2) to prepare, publish, and distribute (free or for sale) reports and maps of the state's geology, mineral resources, and physical features; and 3) to provide information, advice, and services related to the geology, mineral resources, and physical features of the state. The agency's mission is to "promote the beneficial and environmentally sound use of Wyoming's vast geologic, mineral, and energy resources, while helping protect the public from geologic hazards." By providing accurate information and expanding knowledge through the application of geologic principles, the WSGS contributes to the economic growth of the state and improves the quality of life of Wyoming's residents. WSGS hydrogeologists conduct research; compile data; create and distribute maps and reports; and address inquiries to assist citizens, industry, and state and federal agencies in planning, decision making, and analysis of groundwater and surface water issues.

The USGS provides data, maps, reports, and other scientific information to help individuals and local and state governments manage, develop, and protect the water, energy, mineral, and land resources of Wyoming and the United States. The agency's mission is to "provide reliable scientific information to describe and understand the earth; minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect our quality of life." To meet these goals, the USGS employs experienced scientists and support staff from a wide range of earth and life science disciplines.

WRDS is a clearinghouse for hydrological data. WRDS is funded by the WWDO to provide a variety of services, including the online provision of groundwater resources information, maps, and publications.

The SEO and WWDO cooperate on many projects. SEO personnel attend meetings on river basin planning and other WWDC projects. WWDC-funded groundwater development projects generally require permits from both the SEO and WDEQ (K. Clarey, WWDO, pers. commun.).

1.3 Legal and institutional framework

Wyoming laws that govern the appropriation, development, and beneficial use of water resources are based on the doctrine of prior appropriation, commonly stated as "first in time is first in right." This means that, during periods of limited supply, the first party to put a source of water to beneficial use has a "priority" water-right honored prior to those of other, later users. An exception is that municipalities can obtain water-rights from earlier priority uses through eminent domain (Wyoming State Statutes 1-26). Because all waters within Wyoming are property of the state, a water-right does not grant ownership, but only the right to use water for beneficial purposes. Use of water resources for domestic and livestock purposes customarily take precedence over other uses. In Wyoming, water-rights are attached to the land and can be transferred. The laws and regulations pertaining to the appropriation, development, and beneficial use of groundwater are administered by the SEO and Board of Control comprised of the superintendents of the four state water divisions and the State Engineer. The entire Bear River Basin area is included in SEO Water Division IV. A comprehensive discussion of the laws that govern Wyoming water resources is provided online at: http://seo.state.wy.us/PDF/b849r.pdf

1.3.1 Wyoming water law – groundwater appropriation, development, and use

Groundwater within the state is owned and controlled by the state of Wyoming. Under Wyoming law, groundwater includes any water (including geothermal waters) under the land surface or under the bed of any body of surface water. The SEO is responsible for the permitting and orderly development of groundwater in

Wyoming and for protecting groundwater resources from waste and contamination. The updated Wind/Bighorn River Basin Water Plan (MWH and others, 2010) provides the following discussion of Wyoming water law specific to groundwater:

> "Wyoming's groundwater laws were originally enacted in 1945 and amended in 1947. These laws were replaced by new groundwater laws on March 1, 1958, which were then amended in 1969. Groundwater is administered on a permit basis. The acquisition of groundwater rights generally follows the same permitting procedures as surface water rights, except that a map is not required at the time of permit application. Applications are submitted to and approved by the SEO prior to drilling a well. With the completion of the well and application of the water to a beneficial use, the appropriation can then be adjudicated. The issuance of well permits carries no guarantee of a continued water level or artesian pressure."

> "As with surface water rights, groundwater rights are administered on a priority basis. For all wells drilled prior to April 1, 1947, a statement of claim process was followed to determine the priority date of the well. For wells drilled between April 1, 1947 and March 1, 1958, the priority date is the date the well was registered. For wells drilled after March 1, 1958, the priority date is the date the application was received at the WSEO."

> "Domestic and stock wells are those wells used for non-commercial household use, including lawn and garden watering that does not exceed one acre in aerial extent, and the watering of stock. The yield from these wells cannot exceed 25 gallons per minute (gpm). Prior to the 1969 amendment, domestic and stock wells were exempt from the requirement to obtain a permit and held a preferred right over other wells. The 1969 amendment established priorities for domestic and stock wells similar to those for other wells. The Groundwater Division also issues permits for spring developments where the total yield or

flow of the spring is 25 gpm or less and where the proposed use is for stock and/or domestic purposes."

1.3.2 Interstate agreements

Although the Wyoming Constitution establishes that all surface water and groundwater within Wyoming's borders is owned by the state, the right to put surface water and groundwater to beneficial use is permitted via water rights issued by the SEO and adjudicated by the Wyoming Board of Control. Surface water resources of Wyoming are subject to interstate agreements that limit how much streamflow can be depleted before leaving the state. Furthermore, conflicts among users within the state or across state lines can occur where groundwater extraction may affect surface flows. Although interconnection between groundwater and surface water is not currently a significant water-rights issue in the Bear River Basin, it could become a point of contention in the future as the basin's population grows.

To avert present and future conflicts over the allocation and use of flows within the Bear River Basin, the states of Idaho, Utah, and Wyoming agreed to the "Amended Bear River Compact" in 1978. The compact divides water administration in the Bear River among three geographically defined divisions. The Upper Division encompasses the reach of the Bear River that extends from its headwaters in the Uinta Mountains to the Pixley diversion dam in sec. 25, T. 23 N., R. 120 W., of the Sixth Principal Meridian in Wyoming. During a compact defined water emergency in the Upper Division, percentage allocations are made to the Utah and Wyoming Sections and distribution of divertible flow is managed by diversion by the two states. The Central Division extends from below Pixley Dam to the Stewart diversion dam in sec, 34, T. 13 S., R. 44 E., of the Boise Base Meridian in Idaho; during a water emergency, divertible flow is allocated by percentage to Wyoming and Idaho. In the Lower Division, which extends from the Stewart Dam to the Great Salt Lake, divertible flows are allocated by a commission approved delivery schedule.

The portion of the Bear River drainage basin examined in this report consists of the entire Upper Division and those parts of the Central Division that are tributary to the Bear River upstream of the Idaho-Wyoming border (**Fig. 3-1**). **Appendix D** (SEO, 2006) contains a copy of the Amended Bear River Compact (1978). The compact is administered by the Bear River Commission, consisting of three commissioners from each signatory state. The Interstate Streams Division of the SEO, in conjunction with SEO Water District IV staff, administers the provisions of the compact that fall under the authority of the state of Wyoming. A map of the larger Bear River Basin depicting the three divisions can be found online: http://bearrivercommission.org/docs/16thpercent20final.pdf.

Article VI of the compact allocates an additional 13,000 acre-feet annual total of surface and connected groundwater each to Wyoming and that portion of Utah above Stewart Dam for beneficial uses applied on or after January 1, 1976. Historically, Wyoming has used only a small portion of this additional allocation, so it is likely that future groundwater development in the Bear River Basin will be allowed so that Wyoming can utilize the 13,000 acre-feet allocation. In Wyoming, the SEO monitors surface water and connected groundwater depletions of the additional allocation.

1.3.3 Wyoming water law – groundwater quality

The Denver office of the U.S. Environmental Protection Agency (EPA) Region 8 has primary control (primacy) over Wyoming's public drinking water supplies. Wyoming is the only state in which EPA has primacy over drinking water systems. The EPA monitors water quality for the several hundred public water systems in Wyoming. Information on Wyoming's public drinking water systems is available on the EPA Wyoming Drinking Water website: http://www.epa.gov/safewater/dwinfo/wy.html

Except on the Wind River Indian Reservation, the DEQ enforces groundwater quality regulations under the Wyoming Environmental Quality Act, with guidance from the Wyoming Environmental Quality Council. The DEQ administers provisions of the federal Clean Water Act Amendment of 1972 (Section 208) that provide for water quality management by state and local governments, as well as provisions of the Federal Water Pollution Act, by developing a State Water Quality Plan approved by the EPA. In general, operations under the jurisdiction of the Wyoming Oil and Gas Conservation Commission (WOGCC), U.S. Bureau of Land Management (BLM), EPA, or U.S. Forest Service that cause groundwater contamination are referred to the DEQ. The WOGCC has jurisdiction over Class II underground injection wells (**Chapter 5**) dedicated to disposal of produced water from state and federal oil and gas leases.

1.3.4 Other agencies

The U.S. Bureau of Reclamation (BOR), an agency under the U.S. Department of the Interior, oversees and manages water resources specifically related to the operation of numerous water diversions, delivery, storage, and hydroelectric power generation projects built by the federal government throughout the western United States. The BOR cooperates with the SEO and the WWDC (primarily through the SEO) but as a federal agency, has autonomy to execute some programs unilaterally. The BOR coordinates releases from Wyoming's reservoirs with the SEO. (K. Clary, WWDO, pers. commun.). Although not a primary area of concern, the BOR and the following other agencies are occasionally involved in groundwater resource issues:

- Wyoming Department of Agriculture
- U.S. Department of Agriculture and the
- U.S. National Park Service
- U.S Army Corps of Engineers
- U.S. Office of Surface Mining, Reclamation and Enforcement
- U.S Bureau of Ocean Energy Management and the Bureau of Safety and Environmental Enforcement
- U.S Department of Energy
- U.S. Nuclear Regulatory Commission

1.4 Authorship

The principal authors of this Technical Memorandum are:

Karl Taboga, Wyoming State Geological Survey, Laramie, Wyoming
Timothy T. Bartos, U.S. Geological Survey, Wyoming Water Science Center, Cheyenne, Wyoming
Paul Taucher, Energy Compliance LLC, Laramie, Wyoming

Additional authors and coauthors of specific sections of this Technical Memorandum are:

- **Chapter 3:** James Stafford, WSGS, Laramie, Wyoming
- **Chapter 4:** Seth Wittke, WSGS, Laramie, Wyoming
- **Chapter 5:** Keith Clarey, WWDO, Cheyenne, Wyoming; Laura L. Hallberg, and Melanie L. Clark, USGS, WWSC, Cheyenne, Wyoming; James Stafford, WSGS
- **Chapter 7:** Laura L. Hallberg, and Melanie L. Clark, USGS, WWSC, Cheyenne, Wyoming
- **Chapter 8:** James Stafford, WSGS, Laramie, Wyoming
- **Appendix A:** Seth Wittke, WSGS, Laramie, Wyoming
- **Appendix C:** Tomas Gracias, WSGS, Laramie, Wyoming

1.5 Acknowledgements

Chapter 2
Background

Karl Taboga and Paul Taucher

A wide variety of available information was reviewed and compiled for this updated and expanded study of the Bear River Basin groundwater resources. The updated data was obtained from regional and area-specific studies conducted by state and federal agencies in Wyoming, Idaho, and Utah. This chapter discusses the data sources, approach, organization, and computer-based mapping used in this current study and compares them to the previous Ground Water Resource Investigations contained within the 2001 and 2011 Bear River Basin Water Plans (Forsgren and Associates, 2001; Wyoming Water Development Office (WWDO), 2012).

The 2011 Bear River Water Basin Plan (WWDO, 2012) and associated technical memoranda constitute the most recent of the studies completed by the WWDO between 2000 and 2011 for Wyoming's seven major drainage basins. The 2011 plan provides extensive information about the cultural and physical settings of the basin both generally and as they relate to groundwater resources. In order to avoid repetition, the 2011 plan and 2007 Wyoming Framework Water Plan that summarizes and updates the 2001 Bear River Basin Plan – Forsgren and Associates (2001) are cited frequently in this study and where appropriate, links are provided to online information.

2.1 Sources of data

Agencies that contributed data and information for this study include:

BLM	U.S. Bureau of Land Management
EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
	University of Wyoming Libraries
WRDS	University of Wyoming Water Resources Data System
DEQ	Wyoming Department of Environmental Quality
WyGISC	Wyoming Geographical Information Science Center

WOGCC	Wyoming Oil and Gas Conservation Commission
WRRI	Wyoming Water Resources Research Institute
SEO	Wyoming State Engineer's Office
WSGS	Wyoming State Geological Survey
WWDC	Wyoming Water Development Commission
WWDO	Wyoming Water Development Office

2.2 Previous regional-scale investigations

Several surface water and groundwater management studies have been previously conducted for areas contained wholly or partly within the Bear River Basin. The geographic scale of the earlier projects varies considerably. This study builds on those previous compilations. The primary hydrogeologic studies and associated supporting geologic investigations of the basin area are listed below in approximate chronologic order by agency and author(s):

- *U.S. Geological Survey Hydrologic Investigation Atlases*
  1968 - Welder, G.E., 1968, Groundwater reconnaissance of the Green River Basin, southwestern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-290, 1 map on 2 sheets, scale 1:250,000, text 5 p.
  1975 - Lines, G.C., and Glass, W.R., 1975, Water resources of the thrust belt of western Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-539, map scale 1:250,000, 3 sheets.
  1996 - Whitehead, R.H., 1996 Ground water atlas of the United States, Segment 8, Montana, North Dakota, South Dakota, Wyoming: U.S. Geologic Survey Hydrologic Investigations Atlas HA-730-I, 24 p.

- *Basin studies by the University of Wyoming, Water Resources Research Institute, and the Wyoming Natural Resource Board*

  1962 - Dana G. F., 1962, Groundwater reconnaissance study of the State of Wyoming, part 4. Green River basin: Prepared for Wyoming Natural Resource Board, Cheyenne, 355 p.

  1981 - Ahern, J., Collentine, M., and Cooks, S., 1981, Occurrence and characteristics of groundwater in the Green River Basin and Overthrust Belt, Wyoming: Report to U.S. EPA, Contract Number G-008269-79, by Water Resources Research Institute, University of Wyoming, Laramie, Wyoming, Volume V-A and Volume V-B (Pl.s), 2volumes, 123 p.

- *Wyoming State Geological Survey publications*

  1937 - Geological Survey of Wyoming, 1937, Geologic map of Uinta County, Wyoming: Compiled from all available data by the Geological Survey of Wyoming in cooperation with the Wyoming State Planning Board, Geological Survey of Wyoming, map scale 1:253,440 (1 inch = 4 miles), 1 sheet (rolled).

  1993 - Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., *compilers*, 1993, Stratigraphic chart showing the Phanerozoic nomenclature for the State of Wyoming: Geological Survey of Wyoming Map Series 41 (MS-41), no scale, 1 sheet.

  1993 - Royse, F., Jr., 1993, An overview of the geologic structure of the thrust belt in Wyoming, northern Utah, and eastern Idaho: *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., Eds., Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 272-311.

- *U.S. Geological Survey Water Supply Papers, Professional Papers, Scientific Investigation Reports, Scientific Investigation Maps, Open-File Reports, Water Resource Investigations Reports, and Circulars.*

  1906 - Veatch, A.C., 1906, Coal and oil in southern Uinta County, Wyoming: U.S. Geological Survey Bulletin 285-F, Contributions to Economic Geology, p. 331-353.

  1907 - Veatch, A.C., 1907, Geography and geology of a portion of southwestern Wyoming, with special reference to oil and coal: U.S. Geological Survey Professional Paper 56, 26 plates, 178 p.

  1961 - Rubey, W.W., Oriel, S.S., and Tracey, J.I., Jr., 1961, Age of the Evanston Formation, western Wyoming: U.S. Geological Survey Professional Paper 424-B, Geological Survey Research 1961: Short Papers in the Geologic and Hydrologic Sciences, Article 64, p. B153-B154.

  1963 - Robinove, C.J., and Berry, D.W., 1963, Availability of ground water in the Bear River valley, Wyoming, *with a section on* Chemical quality of the water, by J.G. Connor: U.S. Geological Survey Water-Supply Paper 1539-V, 44 p., 2 pl.

  1963 - Robinove, C.J., and Cummings, T.R., 1963, Ground-water resources and geology of the Lyman – Mountain View area, Uinta County, Wyoming: U.S. Geological Survey Water-Supply Paper 1669-E, 1 plate, 43 p.

  1969 - Hansen, W.R., 1969, The geologic story of the Uinta Mountains: U.S. Geological Survey Bulletin 1291, second printing 1975, 144 p.

  1973 – Rubey, W.W., 1973a, Geologic map of the Afton quadrangle and part of the Big Piney quadrangle, Lincoln and Sublette counties, Wyoming: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-686, map scale 1:62,500, 2 sheets.

  1973 - Rubey, W.W., 1973b, New Cretaceous formations in the western Wyoming thrust belt: U.S. Geological Survey Bulletin

1372-I, Contributions to Stratigraphy, 35 p.

1976 - Rubey, W.W., Oriel, S.S., and Tracey, J.I., Jr., 1976, Geologic map of the Cokeville 30-minute quadrangle, Lincoln and Sublette counties, Wyoming: U.S. Geological Survey Open-File Report 76-597 (OFR 76-597), map scale 1:62,500, 1 sheet.

1980 - Oriel, S.S., and Platt, L.B., 1980, Geologic map of the Preston 1° x 2° quadrangle, southeastern Idaho and western Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I-1127, scale 1:250,000, 1 sheet.

1980 - Rubey, W.W., Oriel, S.S., and Tracey, J.I., Jr., 1980, Geologic map and structure sections of the Cokeville 30-minute quadrangle, Lincoln and Sublette counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-1129, map scale 1:62,500, 2 sheets.

1983 – Gibbons, A.B., and Dickey, D.D., 1983, Quaternary faults in Lincoln and Uinta counties, Wyoming, and Rich County, Utah: U.S. Geological Survey Open-File Report 83-288 (OFR 83-288), map scale 1:100,000, 1 sheet.

1985 - Love, J.D., and Christiansen, A.C., *compilers*, 1985, Geologic map of Wyoming: U.S. Geological Survey, map scale 1:500,000, 3 sheets.

1985 - Lowham, H.W., Peterson, D.A., Larson, L.R., Zimmerman, E.A., Ringen, B.H., and Mora, K.L., 1985, Hydrology of Area 52, Rocky Mountain Coal Province, Wyoming, Colorado, Idaho, and Utah: U.S. Geological Survey Water-Resources Investigations/Open-File Report 83-761, Cheyenne, Wyoming, October 1985, 96 p.

1986 - Gibbons, A.B., 1986a, Surficial materials map of the Evanston 30' x 60' quadrangle, Uinta and Sweetwater counties, Wyoming: U.S. Geological Survey Coal Map C-103, map scale 1:100,000, 1 sheet.

1986 – Gibbons, A.B., 1986b, Surficial materials map of the Kemmerer 30' x 60' quadrangle, Lincoln, Uinta, and Sweetwater counties, Wyoming: U.S. Geological Survey Coal Map C-102, map scale 1:100,000, 1 sheet.

1990 – Glover, K.C., 1990, Stream-aquifer system in the Upper Bear River valley, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 89-4173, Cheyenne, Wyoming, 58 p.

1992 - M'Gonigle, J.W., and Dover, J.H., 1992, Geologic map of the Kemmerer 30' x 60' quadrangle, Lincoln, Uinta, and Sweetwater counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-2079, map scale 1:100,000, 1 sheet.

1993 - Smith, M.E., and Maderak, M.L., 1993, Geomorphic and hydraulic assessment of the Bear River in and near Evanston, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 93-4032, 61 p.

1995 - Ogle, K.M., Eddy-Miller, C.A., and Busing, C.J., 1996, Estimated use of water in Lincoln County, Wyoming, 1993: U.S. Geological Survey Water-Resources Investigations Report 96-4162, 13 p.

1996 - Eddy-Miller, C.A., Plafcan, M., and Clark, M.L., 1996, Water resources of Lincoln County, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 96-4246, 131 p, 3 pl.

2000 - Eddy-Miller, C.A., and Norris, J.R., 2000, Pesticides in groundwater - Lincoln County, Wyoming, 1998-99: U.S. Geological Survey Fact Sheet FS-033-00, 1 folded sheet, 4 p.

2004 - Eddy-Miller, C.A., and Remley, K.J., 2004, Pesticides in groundwater - Uinta County, Wyoming, 2002-03: U.S. Geological Survey Fact Sheet 2004-3093, 1 folded sheet, 4 p.

2013 - Eddy-Miller, C.A., Bartos, T.T., and Taylor, M.L., 2013, Pesticides in Wyoming groundwater, 2008–10: U.S. Geological Survey Scientific Investigations Report 2013–5064, 45 p.

- *Wyoming Water Development Commission Studies*

  1991 - Johnson-Fermelia Company, Inc., 1991, Phase 1 report, Cokeville water supply study project level I: prepared for the WWDO, various pagination.

  1992 – TriHydro Corporation, 1992, Phase I report: Level II feasibility study, ground-water alternatives investigation, Cokeville, Wyoming: Consultant's report prepared for the WWDO, Cheyenne, Wyoming, and Forsgren Associates, Evanston, Wyoming; prepared for WWDO, various pagination.

  1993 - Forsgren Associates, 1993a, Cokeville water supply level II study, final report: prepared for the WWDC and the Town of Cokeville, various pagination.

  1993 - Forsgren Associates, 1993b, in association with Chen Northern, Inc., and Trihydro Corporation, Cokeville water supply level II study, supplemental reports: prepared for the WWDC and the Town of Cokeville, Wyoming, various pagination.

  1993 - TriHydro Corporation, 1993, Phase II report, Well construction and testing program, level II feasibility study, Cokeville, Wyoming, *in* Forsgren Associates, 1993, in association with Huntingdon Chen-Northern, Inc., and TriHydro Corporation, Cokeville water supply level II study, supplemental reports: report prepared for the WWDC and the Town of Cokeville, various pagination.

  1995 - TriHydro Corporation, 1995, Level III construction and testing report, Cokeville No. 2 and Cokeville No. 3 municipal water supply wells, Cokeville, Wyoming (draft): prepared for the WWDC and the Town of Cokeville, various pagination.

  1997 - Sunrise Engineering, 1997, Evanston water system master plan level II study: prepared for the WWDO, various pagination.

  2000 - TriHydro Corporation, 2000, Hydrogeologic report: North Uinta County improvement and service district water supply master plan, Uinta County, Wyoming: prepared for the WWDC and the North Uinta County Improvement and Service District, various pagination.

  2000 - Forsgren Associates, 2000, North Uinta County Improvement and Service District water supply master plan level I, final report: prepared for the WWDC and the North Uinta County Improvement and Service District, various pagination.

  2001 - Forsgren Associates, Inc., 2001, in association with Anderson Consulting Engineers, Inc., Leonard Rice Engineers, Inc., and BBC Research & Consulting, Bear River basin plan, final report: prepared for the WWDO, 96 p., Appendices. [http://waterplan.state.wy.us/plan/bear/bear-plan.html]

  2003 - TriHydro Corporation, 2003, in association with Forsgren Associates, North Uinta water supply project level II feasibility study, Bear River, Wyoming, final report: prepared for the WWDC and the North Uinta County Improvement and Service District, various pagination.

  2005 - Sunrise Engineering, 2005, in association with Fassett Consulting, LLC., Evanston/Bear River regional pipeline level II study: prepared for the WWDO, various pagination.

  2007 - WWC Engineering, Inc., 2007, in association with Hinckley Consulting, Collins Planning Associates, Greenwood Mapping, Inc., and States West Water Resources Corporation, Wyoming framework water plan: prepared for the WWDO, Cheyenne, Wy., v. 1 and 2, various pagination. [http://waterplan.state.wy.us/]

  2012 - WWDO, 2012, in association with the State Engineer's Office and

U.W. Water Resources Data System, 2011 Bear River Basin plan update, final report, technical memoranda, GIS products and hydrologic models, various pagination.

2.3 Current WWDC and USGS regional-scale investigations

In addition to these existing studies, the WWDC is conducting a review of the previous Bear River Basin Water Plan (WWDO, 2012) and constructing a hydrological model for surface flows in the basin. The U.S. Geological Survey (USGS) is not currently conducting any specific hydrogeologic investigations in the basin but continues to collect real time streamflow data and periodic water quality at eight USGS stream gaging stations located in the Wyoming Bear River Basin.

2.4 Current Available Groundwater Determination

The previous investigations, that examined the hydrogeology of geographic areas of varying scale that fall partly or entirely within the Bear River Basin were generally based on structural basins, counties, or other specific areas of interest (USGS studies). The study area of this and the previous memoranda (Forsgren Associates, Inc., 2001; WWDO, 2012) include the surface drainages of the Bear River that lie within the borders of the state of Wyoming as well as small watersheds in Idaho and Utah that are tributary to the Wyoming Bear River Basin (**Fig. 3-1**).

A detailed hydrostratigraphy of the Bear River Basin was developed by the USGS for this study based on stratigraphic regions by Love and others (1993). Development of the updated hydrostratigraphy is described in **Chapter 7** and summarized on hydrostratigraphic nomenclature charts (**Pl. 5**), and on **Plate 2**, a surface hydrogeologic map and hydrostratigraphic chart for the overall Bear River Basin.

This updated Available Groundwater Determination provides expanded information on

several topics, developed to more fully characterize the groundwater resources of the Bear River Basin:

- Effects of structure on groundwater distribution and flow (**Section 5.4** and **Chapter 7**).
- Aquifer vulnerability and potential sources of groundwater contamination (**Section 5.6**.
- Comparisons of calculated aquifer-specific recharge volumes with updated precipitation data, and current and projected beneficial uses (**Section 6.2**).
- A basin-wide water balance (**Chapter 8**).
- A detailed listing and summary of historic groundwater development studies by the WWDC in the Bear River Basin (**Appendix B**).
- A list of technical terms and concepts commonly used in groundwater science (**Section 5.1.1**).

2.5 Maps

Progressive improvements in geographic information system (GIS) technology have greatly enhanced the geologist's ability to process and present large, complex, geospatially-linked datasets for natural resource evaluations. To meet the objectives of this updated Available Groundwater Determination, the WSGS and USGS developed a series of maps to present and evaluate the extensive digital data resources available on Bear River Basin groundwater resources. Several maps were generated wholly or primarily from existing GIS databases compiled specifically for this study. Some of the maps and layers were supplemented with information scanned or digitized from existing hard copy maps into GIS-supported formats.

The accuracy of any map or figure depends on the accuracy of the original data and the methods used to process it. Frequently, data processing for large compilations requires correlation between multiple, disparate datasets. The limitations of the data used in digital mapping make it necessary for the analyst to provide the reader with interpretive qualifications regarding the reliability of the produced maps and Figures. This memorandum

provides discussions of data limitations and cites data sources for each map and figure presented.

Additionally, *metadata* (qualifying information on the GIS datasets) is commonly furnished along with the GIS data. Metadata provides structured and detailed descriptive information about the data resources used to develop GIS map layers. Metadata facilitates the understanding, use, and management of the data by defining its sources, locations, formats, attributes, processing, limitations, disclaimers, etc. Where appropriate, the metadata includes contact information where additional information can be obtained. The metadata associated with the Bear River Basin maps are provided on-line at http://waterplan.state.wy.us/plan.

WSGS and USGS generated the maps for this study in two formats. Plate-scale maps use 1:380,000 scale (1 inch = 6 miles). Figure-scale maps use variable scales that allow the maps to fit either 8½ × 11-inch, or 11 × 17-inch sheets depending on the amount of data presented and readability considerations.

Chapter 3
Description of the Study Area

Karl Taboga, James Stafford and
Paul Taucher

This study examines groundwater resources that underlie the Bear River drainage basin in Wyoming as well as areas in Idaho and Utah that are tributary to the Wyoming part of this basin (**Fig. 3-1**). The Bear River Basin covers approximately 1,494 square miles (0.95 million acres) or 1.5 percent of Wyoming's surface area. The tributary watershed in southeastern Idaho is small, about 18 square miles (0.01 million acres). Approximately 1,112 square miles (0.71 million acres) of tributary watershed are located in northeastern Utah. In Wyoming, the Bear River Basin includes 23 percent of Uinta County and 24 percent of Lincoln County. In Utah, the tributary watershed covers 15 percent of Summit and 75 percent of Rich counties. Unless specific references are made to the Utah and Idaho tributary areas, it can be assumed that references to the Bear River Basin in this memorandum include only the Wyoming portion of the watershed defined above.

Although, the Bear River Basin encompasses about 1.5 percent of Wyoming's total surface area, it serves as home to approximately 14,500 people or about 2.4 percent of the state's current population (2010 census). The Bear River Basin contains three incorporated municipalities (Evanston, Cokeville, and Bear River); a U.S. Census Designated Place (CDP), Taylor; approximately 2000 people live in rural areas. The index map in **Figure 3-1** shows townships, major roads, and incorporated municipalities within the Bear River Basin.

3.1 Physiography, landforms, topography, and surface drainage

The Bear River drainage basin is located almost entirely within the Middle Rocky Mountain Physiographic Province; a small part of the basin falls within the Wyoming Basin Province just to the east and northeast of the point where the river crosses Wyoming's southern border. Major drainages, reservoirs, and physiographic features of the Bear River Basin are shown on **Figure 3-2**. A map of the physiographic provinces of Wyoming can be found on the WSGS website at http://www.wsgs.uwyo.edu/Research/Geology/images/Final/Elevations.pdf.

The overall physiography of the Bear River Basin consists of a deeply eroded geologic foundation composed of arcuate belts of strike ridges and valleys. This system of belts, known as the Thrust, or Overthrust, Belt of eastern Idaho, northern Utah and western Wyoming was formed over 70 million years during the Sevier Orogeny (125 – 55 million years ago (Ma)). During that time, rocks of Paleozoic and Mesozoic age were pushed eastward along low angle, imbricated (overlapping), westward-dipping thrust faults. This resulted in the formation of five thrust systems (**Fig. 4-1**). The extent of the Bear River drainage basin examined in this study (**Fig. 3-1**) encompasses portions of all five Sevier thrust systems. The Wyoming portion of the Bear River Basin includes the three eastern-most thrust systems: the Crawford, the Absaroka, and the Darby.

Following the thrust systems, a phase of geologic extension started in the late Eocene, about 35 - 40 Ma, and continues to the present. The extension formed numerous normal faults that shape the foundation of the Bear River valley and its tributary drainages. During the Sevier Orogeny and the more recent period of geologic extension, erosion, mass wasting, and fluvial processes wore down the highlands and deposited sediments in the valleys. These processes, combined with concurrent and continued faulting, resulted in the present physiography characterized by north-south trending mountain ranges with alternating valleys of variable areal scale and elevation. In Wyoming, elevations in the Bear River Basin range from 6,055 feet above mean sea level where the Bear River crosses the Wyoming-Idaho state line to 10,761 feet at Mount Isabel (Wyoming Water Development Office (WWDO), 2012). Detailed discussions of the geography of the Bear River Basin are provided in the 2011 Bear River Basin Plan (WWDO, 2012) and can be accessed at http://waterplan.state.wy.us/plan/bear/2011/finalrept/finalplan.html.

Surface drainage in the Bear River Basin is controlled by topography. Perennial streams receive a large percentage of their source waters from overland flow associated with snowmelt and rainfall that originate in semi-humid and
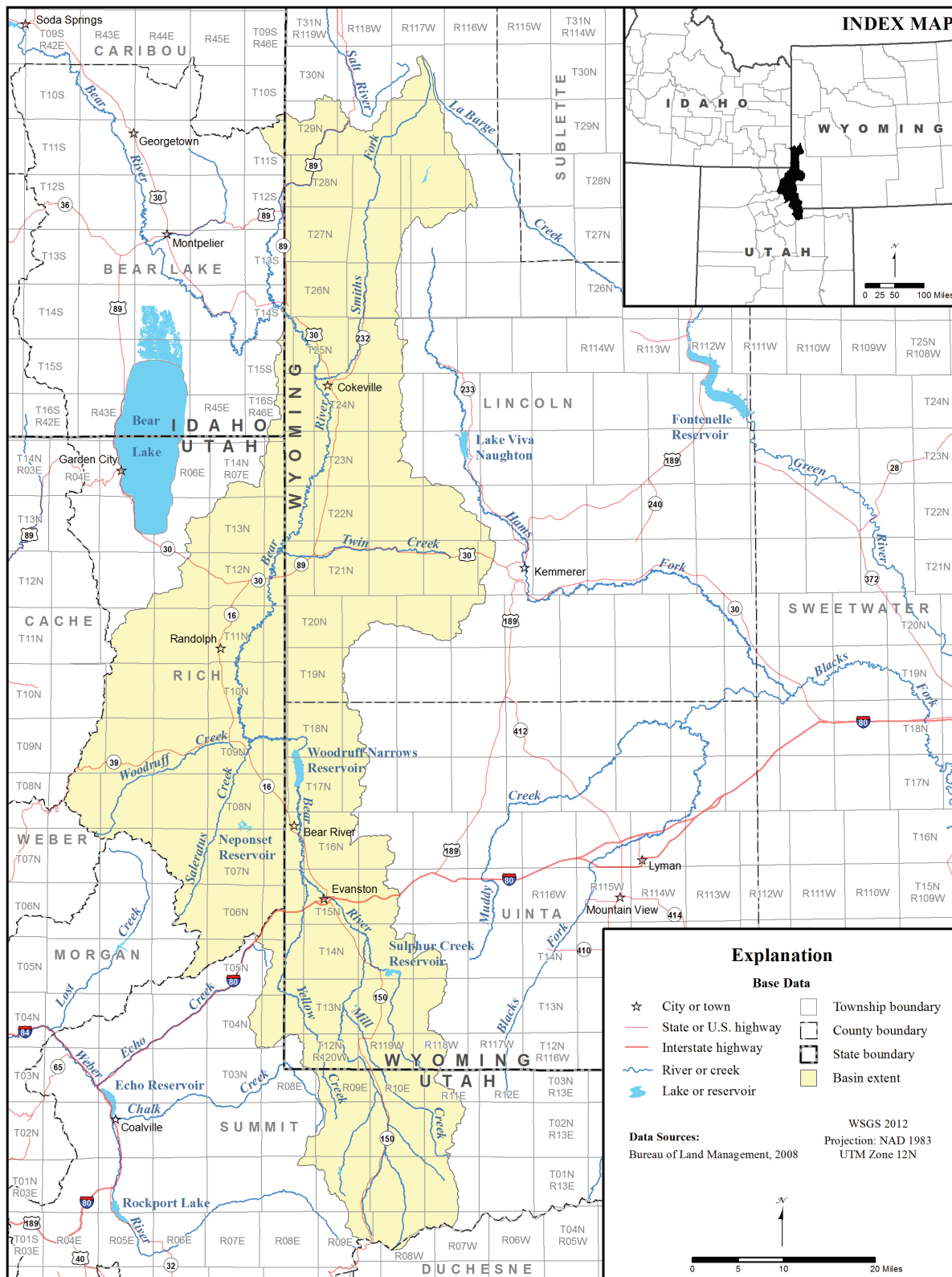
Figure 3-1. Municipality, road, township, and range index map, Bear River Basin.
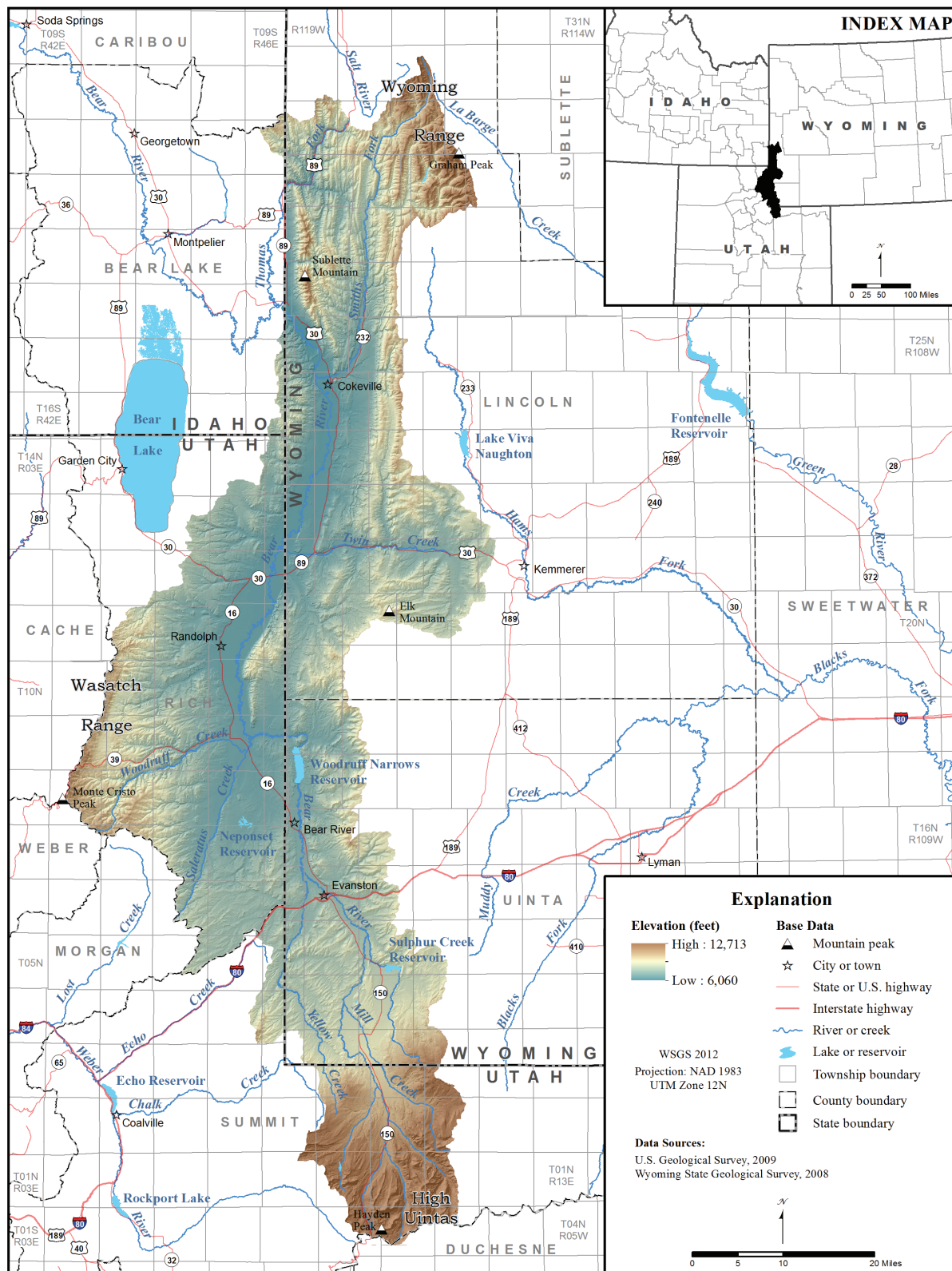
Figure 3-2. Physiographic features, drainages, and bodies of water, Bear River Basin.

humid mountainous headwater regions and from persistent baseflow (WWDO, 2012). Most ephemeral flow occurs in response to springtime snowmelt and to intense, short duration rainfall events characteristic of transient convective thunderstorms. Streamflows are also affected by vegetation, temperature, manmade diversions, and complex interconnections with groundwater.

Major drainages, reservoirs, and physiographic features of the Bear River Basin are shown on **Figure 3-2** and **Plate 1**. The basin encompasses the Bear River and its headwater drainage system. The Bear River is the major tributary to the Great Salt Lake. The mainstem of the Bear River begins at the confluence of Hayden Fork and Stillwater Fork in Summit County, Utah. Primary tributaries that confluence with the Bear River in Wyoming include Sulphur, Bridger, and Twin creeks and Thomas and Smith's forks. Woodruff Creek and Saleratus Creek are Utah tributaries to the Bear River. The distal divides of these drainages define the limits of the Bear River Basin study area.

3.2 Climate, precipitation, and vegetation

Climate within the Bear River Basin is primarily a function of elevation, to a lesser degree latitude and topography. Climate types range from semi-arid continental within the basin interiors, to humid-alpine in the bordering mountains. The mountain ranges capture much of the atmospheric moisture through orographic uplift, increasing annual precipitation in the mountainous regions while substantially decreasing precipitation in the basin interiors. Temperature varies by season from well below 0°F in the winter to more than 100°F in the summer. Annual precipitation increases with surface elevation (**Fig. 3-3**) and can exceed 40 inches a year in the high mountain headwater areas near Smith's Fork; average annual precipitation for the entire basin is 21 inches (PRISM, 2013). Most precipitation within the basin occurs as snowfall during the winter and early spring and as convective thunderstorms during late spring and summer months (Ahern and others, 1981).

The distribution of the diverse vegetation within the Bear River Basin is strongly influenced by elevation, soil type, exposure, and precipitation. In Wyoming, the dominant habitat system is sagebrush steppe/ shrubland, where the dominant vegetation consists of mixed prairie grasses and shrubs (primarily sagebrush). Other widespread habitat types include forest and woodland, agriculture – pasture hay, grasslands, and riparian areas (U.S Fish and Wildlife Service, 2013) Cottonwood and Russian olive trees are found along rangeland drainages where elevated soil moisture levels are maintained by perennial or frequent ephemeral streamflows. Fertile bottomlands along the perennial streams have been converted to irrigated cropland. Major crop producing areas are located along the Bear River mainstem, Sulphur and Mill creeks, and Thomas and Smith's forks (Forsgren and Associates, 2001). The abundance of grasses, shrubs, a variety of woodland trees (primarily conifers), and other species generally increases with altitude and increased annual precipitation up to timberline, above which vegetation is alpine tundra species of lichens, low shrubs, and grasses. A map illustrating the general distribution of vegetation types in the Bear River Basin is provided online in the U.S Fish and Wildlife Service website at http://www.fws.gov/mountain-prairie/planning/lpp/ut/brr/brr.html.

3.3 Population distribution, land use, and land ownership

U.S. Census Bureau data does not provide high resolution population numbers by river basin. Reasonable estimates can be made, however, by processing the most recent census data (U.S. Census Bureau, 2010) for Wyoming counties and municipalities. Using this approach, it is estimated that the 2010 population of the Bear River Basin was approximately 14,500 with about 86 percent residing in cities and towns, and rural populations accounting for the remainder. Every community within the Bear River Basin is located along or within a few miles of the river. While the Bear River Basin encompasses approximately 1.5 percent of the land in Wyoming, in 2010 it contained about 2.4 percent of the state's
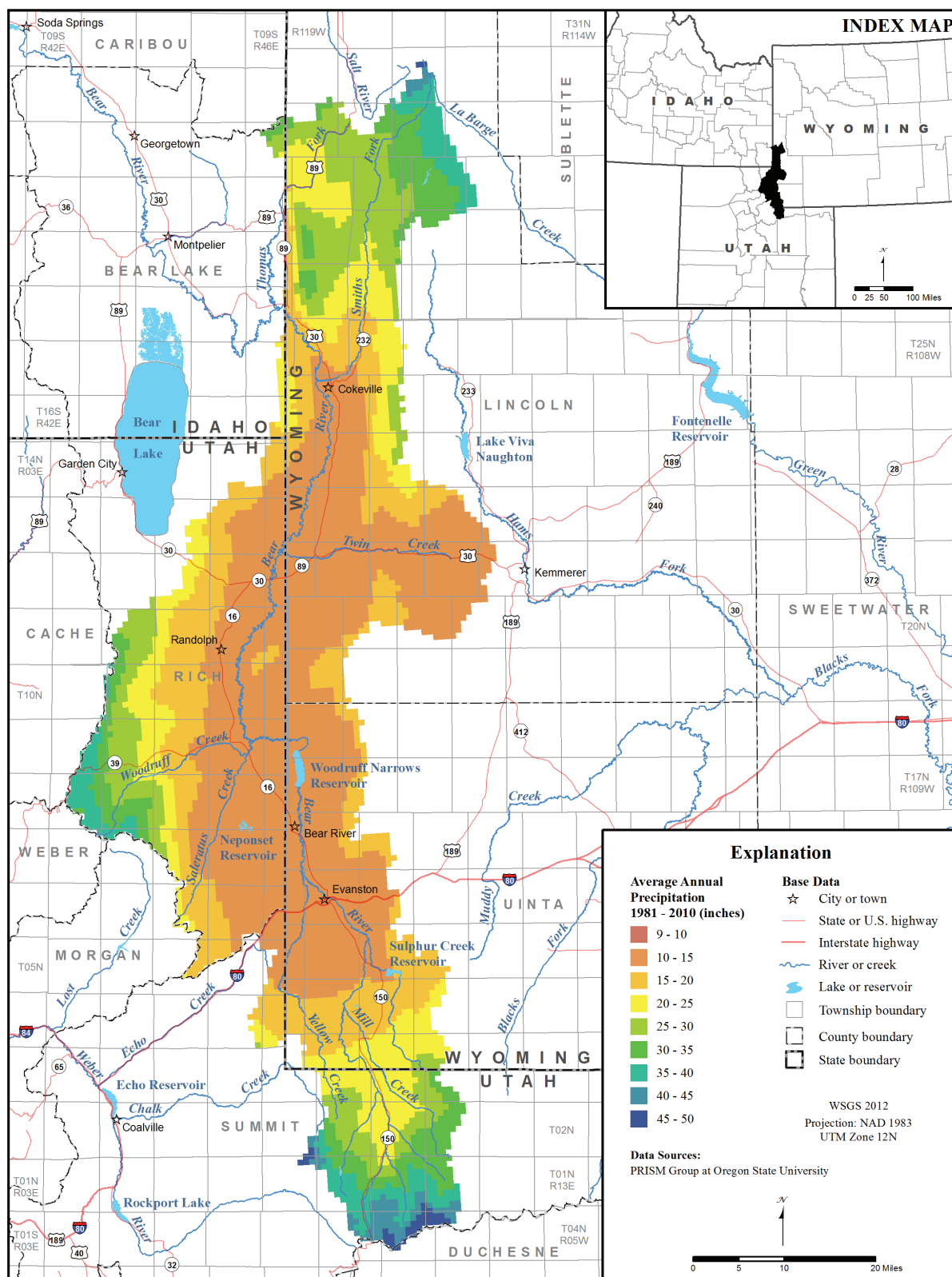
Figure 3-3. Average annual precipitation (1981 - 2010), Bear River Basin.

The map includes the following labels and features:

INDEX MAP — IDAHO, WYOMING, UTAH with scale 0 25 50 100 Miles

Counties and regions: CARIBOU, BEAR LAKE, CACHE, RICH, WEBER, MORGAN, SUMMIT, DUCHESNE, UINTA, LINCOLN, SUBLETTE, SWEETWATER

Cities/towns: Soda Springs, Georgetown, Montpelier, Garden City, Randolph, Woodruff, Bear River, Evanston, Cokeville, Kemmerer, Coalville

Water features: Bear River, Bear Lake, Thomas Fork, Salt River, La Barge Creek, Smiths Fork, Twin Creek, Hams Fork, Green River, Blacks Fork, Fontenelle Reservoir, Lake Viva Naughton, Woodruff Narrows Reservoir, Neponset Reservoir, Sulphur Creek Reservoir, Echo Reservoir, Rockport Lake, Chalk Creek, Yellow Creek, Muddy, Mill Creek, Saleratus Creek, Lost Creek, Weber River

Highways: 36, 30, 89, 232, 233, 16, 39, 189, 240, 372, 28, 412, 150, 65, 32, 40, I-80, I-84

Township markers: T09S R42E, T09S R46E, R119W, T31N R114W, T16S R42E, T14N R03E, T25N R108W, T10N, T20N, T17N R109W, T05N, T02N, T01N R13E, T01N R03E, T01S R03E, T04N R05W

Explanation

Average Annual Precipitation 1981 - 2010 (inches)

- 9 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- 30 - 35
- 35 - 40
- 40 - 45
- 45 - 50

Base Data

- ☆ City or town
- State or U.S. highway
- Interstate highway
- River or creek
- Lake or reservoir
- Township boundary
- County boundary
- State boundary

WSGS 2012
Projection: NAD 1983
UTM Zone 12N

Data Sources:
PRISM Group at Oregon State University

0 5 10 20 Miles

population. Additional detailed information on the demographic conditions of the basin can be found online in the previous 2006 Bear River Basin Final Report at http://waterplan.state.wy.us/plan/Bear/finalrept/Final_report.pdf.

Land use in the Bear River Basin is controlled primarily by elevation, climate, the distribution of surface waters, precipitation, and the location of mineral resources. Above timberline, the alpine lands are generally used for recreational purposes. At lower elevations, thickly forested areas are utilized for recreation and limited (mostly historic) logging. Grazing is the dominant use for rangelands, foothills, and riparian areas. Agriculture plays a significant role in the basin; approximately 6.6 percent (63,900 acres) of its surface area consists of irrigated cropland (WWC Engineering, Inc. and others, 2007).

Croplands are located primarily along the rivers and major streams where irrigation with surface water is possible. Most of the basin lowlands are covered sparsely with grasses, sagebrush, and other shrubs and are amenable for grazing. The locations of active and historic mineral development properties are described in **Section 5.6.2** and shown in Figures contained in that section.

Approximately 54.7 percent of the land area of the Bear River Basin is federally owned. In general, federal land is controlled or managed by the U.S. Bureau of Land Management within the basin lowlands and by the U.S. Forest Service in the forested mountain lands. Privately owned lands, concentrated along rivers and streams, constitute about 37.5 percent of the land in the basin; 7.7 percent is owned by the state of Wyoming and less than 1 percent is owned or managed by other entities. A map of state, federal, and private land ownership in Wyoming is available online via the 2007 Statewide Water Plan Online Presentation Tool at http://waterplan.wrds.uwyo.edu/fwp/Figures/pdf/Fig3-2_3-3.pdf.

Chapter 4
Geologic Setting

Seth Wittke

In Wyoming, the Bear River Basin drainage comprises approximately 24,106 square miles (15.43 million acres), encompassing the western edge of the state, bordering Utah and Idaho. The geologic setting for the Wyoming part of the basin is complex, including three major thrust sheets related to the Sevier Orogeny and subsequent extensional reactivation of several thrust planes during the Quaternary. A complete description of the geologic framework of the Bear River Basin must include summary accounts of the assemblages of geologic and hydrogeologic units and structural elements that define each of their geometry. To accomplish this, an extensive set of figures and maps, presented as plates, are included in this report:

Plate 1 illustrates the bedrock geology of the Bear River Basin in Wyoming, Utah, and Idaho overlain on a base map that shows highway, township, state and county data. Inset maps present the elevations of the Precambrian basement and lineaments (linear geologic features). **Appendix A** contains detailed descriptions of the geologic units shown in **Plate 1**.

Plate 2 displays an outcrop map of hydrogeologic units in the Bear River Basin developed by correlating the geospatial data of hydrogeologic units with hydrostratigraphic nomenclature charts (**Pl. 5**). Individual Bear River Basin aquifers are discussed in detail in **Chapter 7**.

Figure 4-1 illustrates thrust sheet and fault locations in the basin; Five cross sections (**Figs. 4-2** through **4-6**), included at the end of this chapter, show geologic features at selected locations (**Fig. 4-1**). Isopach maps with substantial coverage of the major aquifers in the Bear River Basin are not available.

4.1 General geologic history (Ahern and others, 1981)

The Bear River Basin contains rocks in age from Cambrian to Holocene sediments that overlie a Precambrian basement made up of igneous and metamorphic rocks. The geologic history relevant to groundwater resources of the Bear River basin is as follows:

Paleozoic rocks consist mainly of calcareous passive margin sediments. The calcareous formations are composed of crystalline dolomite and limestone. These formations generally lack solution zones, with the exception of the Madison Limestone. Quartzite, sandstone, conglomerates, mudstone, siltstone, and shale interbed within the Paleozoic carbonates.

Mesozoic sediments are typically clastic, deposited in continental shelf environments. Units in the Triassic up to the Cretaceous Mesaverde Formation are predominately shale mudstone and siltstone. However, limestone, dolomite, and sandstone also occur. The Mesaverde Formation and other rocks in the Upper Cretaceous generally include sandstone, siltstone, and shale with interbedded coal and conglomerate units.

Cenozoic rocks consist of complexly intertonguing fluvial and conglomeritic rocks. Late Paleocene and Eocene rocks are primarily mudstone and sandstone, becoming more tuffaceous towards the Miocene. Miocene and Pliocene rocks consist primarily of conglomerates, claystone, and sandstone. Quaternary rocks consist of unconsolidated sand, clay, and gravels. The unconsolidated units have numerous sources, including glacial, colluvial, and fluvial depositional facies.

4.2 Structural geology

The Bear River Basin consists of two, dominant structural features, the Thrust (or Overthrust) Belt and the Uinta Mountains. The Thrust Belt is a major continental feature, extending from British Columbia to the Uinta Mountains in Utah. The Uinta Mountains are an east-west trending range of Laramide age (35 – 80 million years ago (Ma)) that stretch eastward from the Wasatch Range in the west to the Sand Wash and Piceance basins in Colorado.
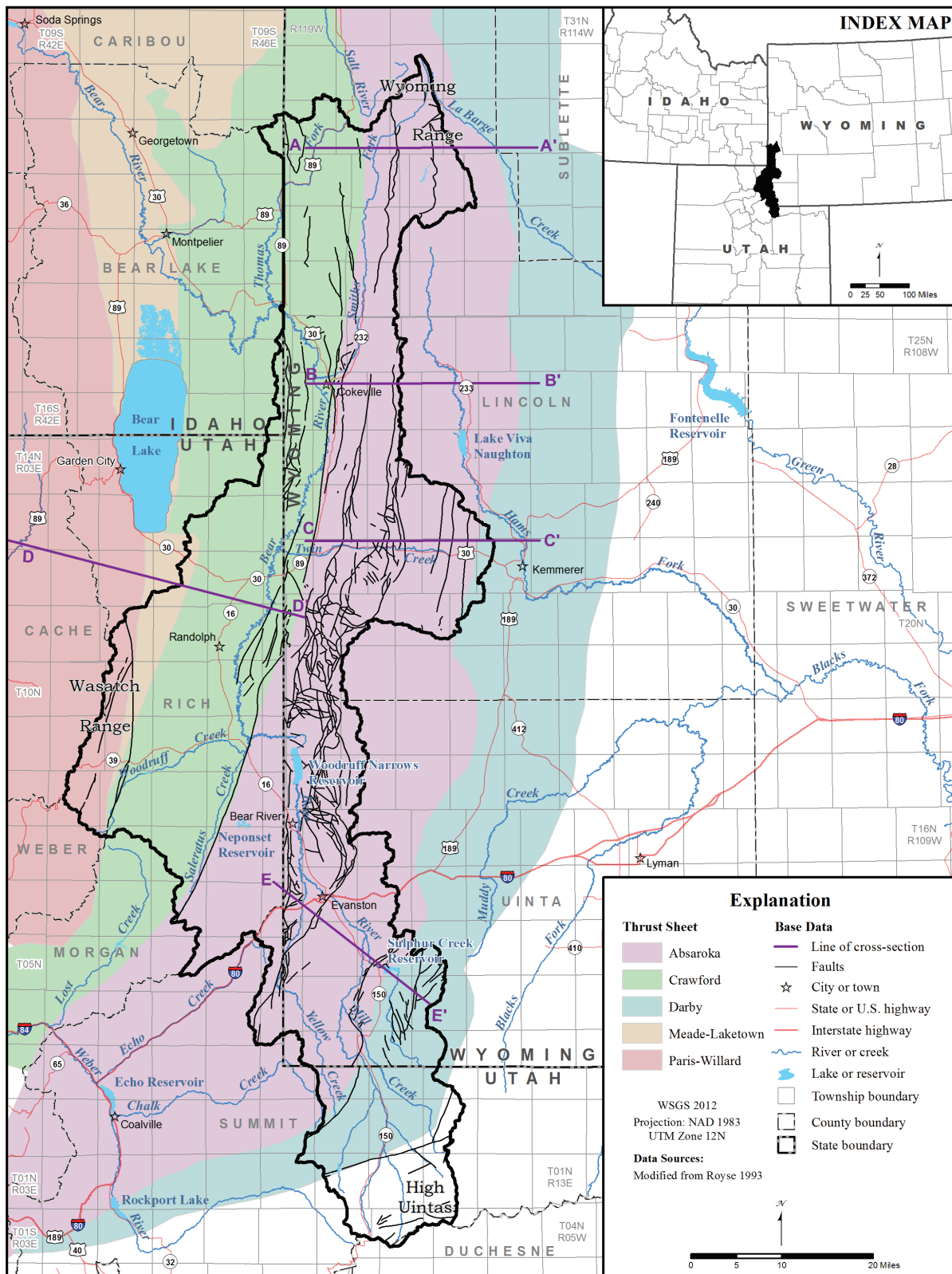
Figure 4-1. Geologic features in the Bear River Basin.

4.3 The Thrust Belt (Ahern and others, 1981)

The thrust belt in the Bear River Basin consists of an expanse of on-strike valleys and ridges with significant topographic relief—up to 1,000 feet per mile in the north. Generally, Paleozoic and Mesozoic rocks were pushed eastward along a series of low-angle, westward-dipping, imbricated faults, creating significant thrust sheets. Stratigraphic displacement along the thrust faults range from 20,000 to 40,000 feet each. Numerous second-order thrusts exist within each sheet. The sediments within each thrust sheet are intensely folded, especially in the northern portion of the basin, and in some cases strata are overturned. Major breccia zones do not exist, and the rocks are not metamorphosed. The rocks generally maintain superposition, suggesting the thrusting occurred along bedding planes. The sub-parallel ranges are bound on the east by thrust faults and on the west by younger, high-angle normal or reverse faults that are down-drop to the west. Some of the normal faults show Holocene aged displacement, including the Bear River fault zone and the Rock Creek Fault.

The formation of the Thrust Belt began during the Sevier orogeny (140 – 50 Ma). All five main thrust systems exist within the Wyoming part of the Bear River Basin and the Utah and Idaho headwater areas (**Fig. 4-1**). From oldest to youngest (west to east) they are the Paris-Willard, the Meade-Laketown, the Crawford, the Absaroka, and the Darby thrust systems.

4.3.1 Paris-Willard Thrust System (Royse, 1993)

The Paris-Willard Thrust System is the most westward, and oldest, of the thrust systems in the Overthrust Belt. It is also the highest structural thrust in the system.   Only a small section of the thrust encompassing the Bear River Range is located within the Bear River Basin. The fault merges with the Meade-Willard Thrust System in the basin, cutting lower Paleozoic rocks in the Bear River Range. The merge also makes a total offset

difficult to determine, but literature suggests offset of about 15 miles.

4.3.2 Meade-Laketown Thrust System (Royse, 1993)

The Meade-Laketown Thrust System in the western most portion of the basin bounds the eastern flank of the Wasatch Range. The Laketown portion of the Meade-Laketown Thrust System is located in the Bear River Basin, and includes Silurian dolomite, not found in the thrust systems to the east. The Laketown thrust is covered by Neogene fluvial beds. The emplacement of the Meade-Laketown Thrust System may be responsible for the conglomerates found in the Cretaceous Frontier Formation in the Bear River Basin.

4.3.3 Crawford Thrust System (Royse, 1993)

The Crawford Thrust System in the center of the basin dictates the majority of the basin's structure. The Crawford system thrusts Cambrian rocks over Upper Cretaceous rocks and is thought to share a common Cambrian detachment zone with the Absaroka thrust to the east. Jurassic evaporite beds act as major detachment horizons for fault offset. Displacement along the Crawford thrust is up to 20 miles in the vicinity of the Crawford Mountains and decreases to the north. The zone between the Crawford and Laketown thrust systems contains a number of thrust faults and folds in Triassic and Jurassic rocks east of Bear Lake valley.

4.3.4 Absaroka Thrust System (Royse, 1993)

The Absaroka Thrust System bounds the basin to the east, influencing the structure in the Twin Creek headwaters and near Sulphur Creek Reservoir. The Absaroka Thrust System cuts from a Cambrian to a Cretaceous detachment along a long lateral ramp. Displacement along the Absaroka Thrust System is up to 28 miles in places, decreasing to the north and south. The zone between the Absaroka and Crawford thrust systems contains numerous thrust faults and folds

in Cretaceous and Jurassic rocks along the Smith's Fork.

4.3.5 Darby Thrust System (Royse, 1993)

The Darby Thrust System is the youngest and easternmost in the Overthrust Belt. The Darby thrust stretches northward from the Uinta Mountains to the Gros Ventre Range, showing an overall offset of up to 18 miles. Only a small portion of the southern edge of the Darby Thrust is found in the Bear River Basin, where the thrust fault intersects the main thrust of the Uinta Mountains. The thrust places lower Paleozoic rocks over the Archean basement.

4.4 Uinta Mountains (Hansen, 1969)

The western Uinta Mountains in northeastern Utah are an east-west trending mountain range approximately 60 miles long in northeastern Utah. Rocks in the western Uinta Mountains range from Precambrian to Quaternary in age. The Uinta Mountains were emplaced as an asymmetric anticline in the late Cretaceous during the Laramide Orogeny. The Uinta anticline was thrust northward, forming the North Flank reverse fault. There are numerous subsidiary faults within the Uinta Mountains, creating broad zones of brecciated and fractured bedrock. Subsequent glacial activity in the high Uintas deposited large expanses of unconsolidated glacial debris across much of the western Uinta Mountains.

4.5 Mineral resources

Figures 5-4, **5-7**, **5-8**, and **5-9** show the distribution of oil and gas operations and other active and historic mineral development locations within the Bear River Basin (**Section 5.6.2**). Mineral development operations require the use of groundwater and may create potential avenues for groundwater contamination. Even in areas without development, the presence of some naturally occurring minerals such as those that contain uranium, arsenic, and hydrocarbons, can, at significant concentrations, negatively impact groundwater quality. Some small communities

in the northern part of the Platte River Basin have had to develop mitigation plans to address exceedances for naturally occurring radium, uranium and/or arsenic in their public water systems (WWC, 2011; Olsson Associates, 2008).

Significant quantities of oil and gas have been developed in the Bear River Basin primarily in the areas around Evanston, including the Bear River Divide and drainages west of Evanston (**Fig. 5-4**). **Figure 5-7** shows that minimal coal, uranium, and metal mines exist in the Bear River Basin. Mapped coal mines are primarily historic pit mines, while a single historic uranium mine/pit was located near Sulphur Creek reservoir.

The Wyoming State Geologic Survey (WSGS) has evaluated many Wyoming sites for potential mineral development. These include precious metals (Hausel, 1989, 2002), gemstones (Hausel and Sutherland, 2000), base metals (Hausel, 1993, 1997), industrial minerals (Harris, 1996), coal (Jones and others, 2011), coal bed natural gas (WSGS, 2005), and petroleum (Lynds, 2013). Mineral development in the Bear River Basin as a source of potential contamination to groundwater resources is discussed further in **Chapter 5**.

Cross Section A - A'

Index Map and Line of Section

Surface Geology
- Quaternary
- Tertiary
- Mesozoic
- Paleozoic
- Precambrian

Base Data
- ☆ City or town
- River or creek
- State or U.S. highway
- □ Township boundary
- State Boundaries
- County Boundaries

Geologic Units

MESOZOIC

Cretaceous

Kbb	Blind Bull Formation
Kf	Frontier Formation
Kck	Cokeville Formation
Ktf	Thomas Fork Formation
Ks	Smiths Formation
Ka	Aspen Shale
Kbr	Bear River Formation
Kab	Aspen Shale and Bear River Formation
Kg	Gannett Group
Krd	Upper Gannett Group
Kb	Bechler Conglomerate of Gannett Group
Kp	Peterson Limestone of Gannett Group
Ke	Ephraim Conglomerate of Gannett Group
Kbe	Middle and lower Gannett Group

MESOZOIC (cont.)

Jurassic

Jsp	Stump Formation and Preuss Redbeds
Js	Sundance Formation
Jp	Preuss Redbeds
Jt	Twin Creek Limestone

Jurassic and Triassic

JTRn	Nugget Sandstone

Triassic

TRa	Ankareh Redbeds
TRt	Thaynes Limestone
TRw	Woodside Redbeds
TRd	Dinwoody Formation

PALEOZOIC

Permian

Pp	Phosphoria Formation

Permian-Pennsylvanian

PPw	Wells Formation

Pennsylvanian and Mississippian

PMa	Amsden Formation

Mississippian

Mm	Madison Limestone

Mississippian and Devonian

MDd	Darby Formation

Ordovician

Ob	Bighorn Dolomite

/	Fault

Rubey, W.W., Oriel, S.S., and Tracey, J.I., 1980, Geologic map and structure sections of the Cokeville 30-minute quadrangle, Lincoln and Sublette Counties, Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series Map I-1129, scale 1:62,500.

Figure 4-2. Geologic cross section A-A'.

Cross Section B - B'

METERS 3000, 2500, 2000, 1500, 1000, 500, SEA LEVEL

FEET 10,000, 8000, 6000, 4000, 2000, SEA LEVEL

B ... B'

ABSAROKA RIDGE · MAMMOTH HOLLOW · South Fork Mountain · SOUTH FORK THRUST · ABSAROKA THRUST · LAZEART SYNCLINE · BEAVER CREEK THRUST · COMMISSARY THRUST · DEMPSEY BASIN · Beaver Creek · PLATEAU · Hams Fork · HAMS FORK · National Coop Linden 1 · RANGE · TUNP THRUST · ROCK CREEK FAULT · TUNP · SUBLETTE FLAT · Station Butte · Coslett Creek · Cokeville · BEAR RIVER · STOFFER RIDGE FAULT · Roney Creek · Embry Creek · OYSTER RIDGE

Index Map and Line of Section

R119W R118W R117W R116W R115W
T26N T25N T24N T23N T22N
Cokeville · Kemmerer · LINCOLN · Bear River · Smiths Fork · 30

Surface Geology
Quaternary
Tertiary
Mesozoic
Paleozoic
Precambrian

Base Data
☆ City or town
River or creek
State or U.S. highway
Township boundary
State Boundaries
County Boundaries

Geologic Units

CENOZOIC

Quaternary and Tertiary

QTg Older gravel deposits

Tertiary

Tfg Gooseberry Member of Fowkes Formation

Tfs Sillem Member of Fowkes Formation

Twt Tunp Member of Wasatch Formation

Tw Wasatch Formation

Twl Lower member of Wasatch Formation

CENOZOIC AND MESOZOIC

Tertiary and Cretaceous

TKe Evanston Formation

MESOZOIC

Cretaceous

Keh Hams Fork Conglomerate Member of Evanston Formation

Kel Lower member of Evanston Formation

MESOZOIC (cont.)

Kav Adaville Formation

Kh Hillard Shale

Kf Frontier Formation

Ksj Sage Junction Formation

Kck Cokeville Formation

Ktf Thomas Fork Formation

Ks Smiths Formation

Ka Aspen Shale

Kbr Bear River Formation

Kg Gannet Group

Krd Upper Gannet Group

Ke Ephraim Conglomerate

Kdp Upper Gannet Group including Bechler Conglomerate and Peterson Limestone

Jurassic

Jsp Stump Formation and Preuss Redbeds

Jt Twin Creek Limestone

MESOZOIC (cont.)

Jurassic-Triassic

JᴿRn Nugget Sandstone

Triassic

Ra Ankareh Redbeds

Rt Thaynes Limestone

Rw Woodside Redbeds

Rd Dinwoody Formation

PALEOZOIC

Permian

Pp Phosphoria Formation

Permian and Pennsylvanian

PIPw Wells Formation

Pennsylvanian and Mississippian

IPMa Amsden Formation

Mississippian

Mm Madison Limestone

╱ Fault

Rubey, W.W., Oriel, S.S., and Tracey, J.I., 1980, Geologic map and structure sections of the Cokeville 30-minute quadrangle, Lincoln and Sublette Counties, Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series Map I-1129, scale 1:62,500.

Figure 4-3. Geologic cross section B-B".

Cross Section C - C'

Index Map and Line of Section

Geologic Units

CENOZOIC

Quaternary

- Qal — Channel and flood-plain deposits
- Qaf — Alluvium, colluvium, and alluvial fans
- Qd — Talus and sloped rubble
- Qt — Terrace deposits
- Qg — Gravel

Quaternary-Tertiary

- QTg — High terrace deposits

Tertiary

- Tfs — Sillem Member of Fowkes Formation
- Tgr — Main body of Green River Formation
- Tga — Angelo Member of Green River Formation
- Twt — Tunp Member of Wasatch Formation
- Twb — Bullpen Member of Wasatch Formation
- Tw — Main body of Wasatch Formation
- Twl — Lower member of Wasatch Formation
- Twc — Basal Conglomerate Member of Wasatch Formation

CENOZOIC AND MESOZOIC

Tertiary-Cretaceous

- TKe — Evanston Formation

MESOZOIC

Cretaceous

- Keh — Hams Fork Conglomerate of Evanston Formation
- Kav — Adaville Formation
- Kh — Hillard Shale
- Khs — Shurtliff Sandstone Member of Hillard Shale
- Kfu — Frontier Formation, upper unit
- Kfm — Frontier Formation, middle unit
- Kfl — Frontier Formation, lower unit
- Ksj — Sage Junction Formation
- Kck — Cokeville Formation
- Ktf — Thomas Fork Formation
- Ks — Smiths Formation
- Ka — Aspen Shale
- Kbr — Bear River Formation
- Kg — Gannet Group

Jurassic

- Jsp — Stump Sandstone and Preuss Redbeds
- Jt — Twin Creek Limestone

Jurassic and Triassic

- JTRn — Nugget Sandstone

MESOZOIC (cont.)

Triassic

- TRa — Ankareh Redbeds
- TRt — Thaynes Limestone
- TRw — Woodside Red Beds
- TRd — Dinwoody Formation

PALEOZOIC

Permian

- Pp — Phosphoria Formation

Permian and Pennsylvanian

- PIPw — Wells Formation

Pennsylvanian and Mississippian

- IPMa — Amsden Formation

Mississippian

- Mm — Madison Limestone

Mississippian and Devonian

- MDd — Darby Formation

Ordovician

- Ob — Bighorn Dolomite

Cambrian

- Cg — Gallatin Formation

/ — Fault

Rubey, W.W., Oriel, S.S., and Tracey, J.I., Jr., 1975, Geology of the Sage and Kemmerer 15 minute Quadrangles, Lincoln County, Wyoming: Wyoming State Geological Survey, Reprint 38, scale 1:62,500.

Figure 4-4. Geologic cross section C-C'.

Cross Section D - D'

Index Map and Line of Section

Geologic Units

CENOZOIC

Quaternary

| Qa+Qaf | Main and side-stream alluvium and fan deposits |
| Qp+Qab | Provo, Alpine, and Bonneville Formations |

Tertiary

Ts	Salt Lake Formation
Tsd	Diamictite facies
Tf	Fowkes Formation
Tfb	Bulldog Hollow Member of Fowkes Formation
Tw	Wasatch Formation
Tg	Gannett Group

MESOZOIC

Cretaceous

| Ksj | Sage Junction Formation |

Jurassic

| Jsp | Stump Formation and Preuss Redbeds |
| Jt | Twin Creek Limestone |

Jurassic and Triassic

| JTn | Nugget Sandstone |

Triassic

Ta	Ankareh Redbeds
Tt	Thaynes Limestone
Tw	Woodside Redbeds
Twd	Woodside Redbeds and Dinwoody Formation

PALEOZOIC

| Pzu | Paleozoic rocks, undivided |

Permian

| Pp | Phosphoria Formation |

Permian and Pennsylvanian

| PPo | Oquirrh Formation |
| PPw | Wells Formation |

Mississippian

Mu	Mississippian rocks, undivided
Mb	Brazer Dolomite
Ml	Lodgepole Limestone

Mississippian and Devonian

| MDt | Three Forks Formation |

Devonian

Dj	Jefferson Formation
Db	Beirdneau Formation
Dh	Hyrum Dolomite
Dw	Water Canyon Formation

Silurian

| Sl | Laketown Dolomite |

Silurian and Ordovician

| SOf | Fish Haven Dolomite |

PALEOZOIC (cont.)

Ordovician

Ob	Bighorn Dolomite
Os	Swan Peak Quartzite
Og	Garden City Formation

Ordovician and Cambrian

O€s	St. Charles Formation
O€sn	St. Charles Formation and Nounan Dolomite
€sw	Worm Creek Quartzite Member of St. Charles Formation
€ga	Gallatin Limestone
€n	Nounan Dolomite
€b	Bloomington Formation
€bl	Blacksmith Formation
€u	Ute Formation
€l	Langston Dolomite
€g	Geertzen Canyon Quartzite
€gu	Upper Member of Geertzen Canyon Quartzite
€gl	Lower Member of Geertzen Canyon Quartzite

Proterozoic

| Zb | Browns Hole Formation |

| ╱ | Fault |

Dover, J.H., 2007, Geologic map of the Logan 30' x 60' quadrangle, Cache and Rich Counties, Utah, and Lincoln and Uinta Counties, Wyoming: Utah Geological Survey, Miscellaneous Publication 06-8DM, scale 1:100,000.

Figure 4-5. Geologic cross section D-D'.
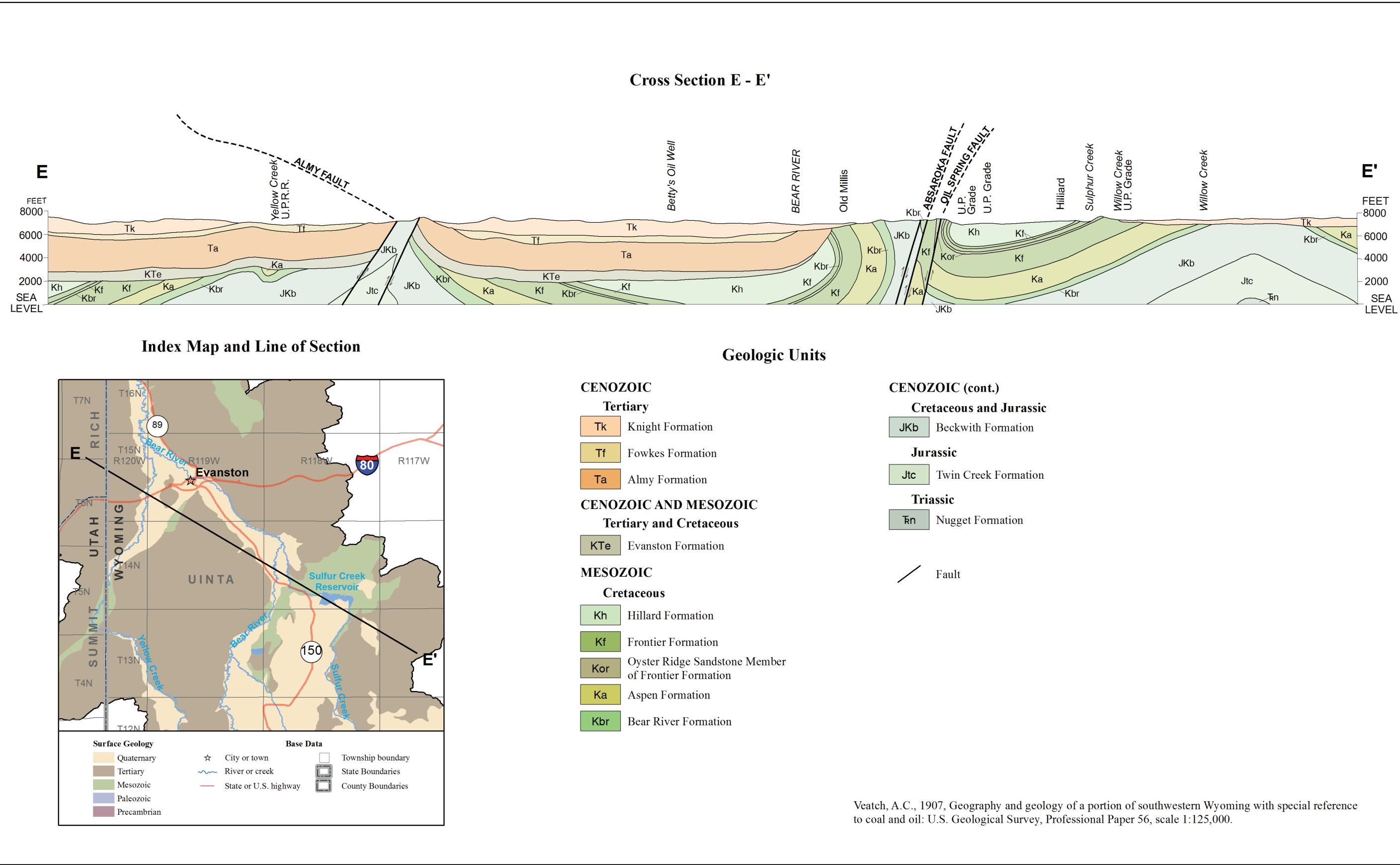
Cross Section E - E'

Figure 4-6. Geologic cross section E-E'.

Index Map and Line of Section

Geologic Units

CENOZOIC

Tertiary

Tk	Knight Formation
Tf	Fowkes Formation
Ta	Almy Formation

CENOZOIC AND MESOZOIC

Tertiary and Cretaceous

KTe	Evanston Formation

MESOZOIC

Cretaceous

Kh	Hillard Formation
Kf	Frontier Formation
Kor	Oyster Ridge Sandstone Member of Frontier Formation
Ka	Aspen Formation
Kbr	Bear River Formation

CENOZOIC (cont.)

Cretaceous and Jurassic

JKb	Beckwith Formation

Jurassic

Jtc	Twin Creek Formation

Triassic

Tᴿn	Nugget Formation

/ Fault

Veatch, A.C., 1907, Geography and geology of a portion of southwestern Wyoming with special reference to coal and oil: U.S. Geological Survey, Professional Paper 56, scale 1:125,000.

Chapter 5

Technical Concepts: Hydrogeology and Groundwater Quality

Paul Taucher, Timothy T. Bartos, Karl Taboga and Jim Stafford

This chapter discusses the technical concepts and terminology used in this study. Additional discussions and illustrations of the concepts commonly used in the study of groundwater resources can be found in U.S. Geological Survey (USGS) Water Supply Paper 2220 (Heath, 1983). *Hydrogeology* is the area of geology that studies the distribution and movement of groundwater through the bedrock and unconsolidated material (including soil) of the Earth's crust. In contrast, the term *geohydrology,* which is often used interchangeably, more properly describes a branch of engineering that studies subsurface fluids. Groundwater hydrology is deemed by the USGS to be the branch of hydrology concerned with the occurrence, movement, and chemistry of groundwater. The study of groundwater resources is an interdisciplinary field that requires extensive knowledge of geology along with an understanding of the basic principles of physics, chemistry, mathematics, biology, and engineering. The hydrogeologist must be able to understand the intricate physical and chemical interactions that occur between groundwater, host rock units, unconsolidated materials, minerals, and the surface environment.

Hydrogeology usually deals with groundwater that is accessible and can be directly used for the benefit of society. Shallow groundwater resources (e.g., water-table and shallow, confined aquifers) and their interactions with surface waters are of interest to geologists, water managers, soil scientists, agriculturalists, hydrologists, water law attorneys, civil engineers, and citizens who use these resources for their water supplies. Groundwater in deeper formations may be relatively inaccessible to the water well driller or, more often, of a quality that is too poor to use for potable water supply. The hydrogeology of these formations may still be important to mineral and petroleum resource geologists, geophysicists, and petroleum engineers. The suitability of groundwater for a particular beneficial use depends primarily on water quality. In this study, groundwater quality is evaluated relative to its suitability for domestic, irrigation, and livestock use, based on the Environmental Protection Agency's (EPA) Safe Drinking Water

Act (SDWA) and the Wyoming Department of Environmental Quality's (DEQ) class-of-use, water-quality standards (**Section 5.5.1**; **Chapter 7**). Aquifer sensitivity, potential sources of groundwater, and state and federal programs designed to characterize and protect groundwater quality in Wyoming are also discussed in this chapter.

5.1 Definitions and concepts

The movement of groundwater through, and its chemical interaction with, permeable earth materials is complex. Highly variable geologic and hydraulic properties within an aquifer control flow, chemical composition, and availability. Fundamentally, groundwater is a slow-moving, viscous fluid that flows through interconnected voids in the host rock along pressure gradients (areas of high hydraulic pressure to areas of lower hydraulic pressure). The voids may consist of pores between individual mineral grains (intergranular space), fractures of varying sizes, faults, dissolution features such as tunnels and caves, vesicles in volcanic rocks, or some combination of these. Voids range in size from microscopic to cavernous. Groundwater chemistry is determined by the mineral composition of the aquifer system and the residence time that the water is in contact with the earth materials through which it flows. Groundwater residence times can range from a few days, to hundreds of thousands of years.

5.1.1 Definitions

The following technical terms and concepts are either used in this study or have been provided to supplement the reader's understanding:

Geologic unit - a geologic formation, member, lens, tongue, bed, flow, other stratigraphic unit or group of rocks that have been correlated, named, and mapped by geologists based on lithological and geospatial continuity and other properties. With the development of Geographic Information Systems (GIS) technology, Wyoming's geologic units have been compiled into a database that can be modified, queried, and mapped based on specified geospatial, physical, and chemical criteria,

such as the hydrologic characteristics described in this study. An additional discussion on geologic units is provided in **Section 5.2**.

Lithostratigraphic unit – a mappable stratigraphic unit defined by lithologic uniformity and continuity. Lithostratigraphic and, to a lesser degree, other stratigraphic units are the most commonly characterized components of geologic units and are generally used in geologic mapping where allowed by the map scale. An additional discussion of lithostratigraphic units is provided in **Section 5.2**.

Hydrogeologic unit – one or more adjacent geologic units, or parts of geologic units (e.g., *lithostratigraphic units*), grouped according to their hydrologic characteristics, such as whether the designated unit functions as an *aquifer* or a *confining unit*.

Aquifer – a *geologic unit*, group of *geologic units*, or part of a *geologic unit* that contains adequate water-saturated and permeable materials to yield sufficient quantities of water to wells and springs (modified from Lohman and others, 1972) with "sufficient" generally defined in terms of ability to meet specified uses. Aquifers both store and convey groundwater. Aquifers are not defined on the basis of geologic unit boundaries, but on the hydraulic characteristics, common recharge-discharge areas, and mechanisms of the units that compose them.

Aquifer system – a heterogeneous body of saturated, interbedded geologic units with variable permeability that operates regionally as a major, integrated, water-bearing *hydrogeologic unit*. An aquifer system comprises two or more smaller aquifers separated, at least locally, by strata with low permeability that impede groundwater movement between the component aquifers but do not preclude the regional hydraulic continuity of the system (modified from Poland and others, 1972). *Aquifers* and aquifer systems are generally anisotropic because of interbedded low-permeability strata (e.g., shale, claystone, mudstone, bentonite, and evaporites).

Most aquifer systems also share the following characteristics:

- Regionally extensive,
- Common recharge and discharge areas and mechanisms,
- Similar hydraulic properties,
- Similar water-quality characteristics,
- Hydraulically isolated from younger and older aquifers/aquifer systems by thick and laterally extensive confining units.

Confining unit – a geologic unit, group of units, or part of a unit with very low *hydraulic conductivity* that impedes or precludes groundwater movement between the *aquifers* it separates or between an *aquifer* and the ground surface. The *hydraulic conductivity* of a confining unit may range from essentially zero to any value substantially lower than that of an adjacent aquifer. Confining units are conventionally considered to be impermeable to groundwater flow, but most leak water at low to very low flow rates. Given large areas and extended periods of time, confining units can ultimately leak significant quantities of water.

Confined aquifer – an *aquifer* overlain and underlain by *confining units* that limit groundwater flow into and out of the aquifer. Confined aquifers are completely saturated and under *artesian* pressure. An aquifer can be semi-confined if there is sufficient leakage through the adjacent *confining unit*(s).

Unconfined aquifer – the water-saturated part of a *hydrogeologic unit* that contains groundwater under atmospheric pressure and thus rises and falls relatively quickly in response to *recharge* (e.g., precipitation, irrigation, or waste disposal) and changes in atmospheric pressure. Unconfined aquifers are generally saturated only in the lower part of the host *hydrogeologic unit*.

Alluvial aquifer – an *aquifer* composed of loose, unconsolidated sediments deposited along a streambed. Alluvial aquifers usually possess high degrees of hydrologic variability over short distances because the component clays, silts, sand, gravel, cobbles, and boulders were unevenly

deposited under shifting climatic and hydrologic conditions.

Bedrock aquifer – an *aquifer* that occurs within a consolidated rock unit. Groundwater is stored and transported within the pores of the solid rock, fractures, solution cavities, or any combination thereof.

Unconsolidated aquifer – a water-bearing unit in loose, uncemented sediments such as sand, gravel, clays, and silts.

Colluvium – Loose, unconsolidated deposits placed primarily by gravity at the foot of a hillslope including deposits such as talus and cliff debris.

Perched groundwater or a *perched aquifer* – an unconfined lens of groundwater, generally limited in lateral extent, lying on top of a *confining unit* in a configuration similar to ponding. Perched groundwater generally occurs at shallower depths hydraulically unconnected to deeper, more laterally extensive, *unconfined* or *confined aquifers*.

Potentiometric surface – a surface that represents the *total head* in an aquifer. Within a *confined aquifer*, it is a conceptual surface defined by the level to which water rises in wells that penetrate that aquifer. Within an *unconfined aquifer,* the conceptual surface corresponds to an actual, physical surface. *Potentiometric surface* has generally replaced the older terms *piezometric surface* and *water table*, and *groundwater surface* is a more up-to-date synonym. The *potentiometric surface* is generally mapped by equal-elevation contours in feet above mean sea level.

Water table – the groundwater surface within an unconfined aquifer under atmospheric pressure. Although the water table is often considered the top of the zone of saturation, it is more correctly considered the surface where pore-water pressure equals atmospheric pressure. While the *capillary fringe* above the water table is saturated, it is below atmospheric pressure and thus fails to meet the definition of the water table. The term water table implies a flat, horizontal surface, but the actual surface is tilted or contoured like the

land surface. In popular usage, the water table is the first occurrence of unconfined groundwater encountered at depth and is generally equivalent to groundwater surface or *potentiometric surface*.

Capillarity – the effect of surface tension and molecular attraction between liquids and solids that causes water within the vadose zone (above the water table) to be at less than atmospheric pressure. Groundwater in the *capillary fringe* immediately above the *water table* will be subject to an upward attraction.

Vadose zone – the depth interval between the ground surface and the water table that can include: 1) unsaturated soils, unsaturated bedrock, and unconsolidated materials such as alluvium, *colluvium*, and weathered bedrock, and 2) the *capillary fringe* immediately above the water table.

Hydraulic gradient – the change in *total head* per unit distance measured in the direction of the steepest slope of the groundwater (potentiometric) surface. Hydraulic gradient has both direction and magnitude and is commonly expressed in feet of elevation change per foot of horizontal distance (ft/ft). The direction of maximum slope on the *potentiometric surface* (or normal to lines of equal elevation on the potentiometric surface), from high to low elevation, indicates the direction that groundwater will flow along permeable, interconnected pathways within isotropic and homogeneous earth materials.

Total head – the height of a column of water above a datum due to a combination of elevation head and pressure head.

Static head or *static water level* – the level of water in a well when neither the well nor surrounding wells are being pumped and the *total head* in the aquifer is generally at equilibrium. Static head or water level is commonly expressed in feet of elevation above mean sea level.

Drawdown – the lowering of the groundwater potentiometric surface (total head) by discharge from an aquifer (pumping or natural discharge)

expressed in feet of water level change. A rise in groundwater level is the opposite of drawdown.

Recharge – water that infiltrates at ground surface, penetrates the *vadose zone*, and reaches the *water table*.

Discharge – groundwater that flows from an aquifer. Discharge from an aquifer can occur naturally by flow into streams or lakes, by leakage into adjacent geologic units, by flow from springs, by near-surface evapotranspiration or artificially, by pumping wells.

Evapotranspiration – the loss of water from the near-surface vadose zone to the atmosphere by the combined processes of evaporation (direct vapor-phase transfer from the soil) and transpiration (transfer through plant root systems and respiration).

Porosity (total) – the proportion of void or open-space volume (e.g., intergranular space, fractures, solution cavities) in a total volume of earth material (e.g., soil, unconsolidated deposit, bedrock), generally expressed as a percentage or decimal fraction.

Effective porosity – the proportion of the *total porosity* in a volume of earth material that is interconnected and allows the flow of groundwater. Water attached to solid surfaces within the interconnected *porosity* decreases effective porosity. Effective porosity is always less than total porosity.

Storage (total) – the total volume of groundwater contained within a volume of earth material – equal to saturated volume times porosity. Storage changes in response to recharge and discharge.

Hydraulic conductivity – the capacity of earth materials to transmit groundwater, expressed as a measure of the amount of water that can flow through the interconnected open spaces of earth materials (often expressed as gallons per day, per square foot: gpd/ft^2), or in terms of velocity (ft/day). Hydraulic conductivity is dependent on the physical characteristics of both the porous earth material and the fluid, and can be as variable as

the lithologies that compose the Earth's crust. This parameter can vary in any direction, but it is commonly much higher parallel to than across stratification.

Permeability – differs from *hydraulic conductivity* in that it depends only on the characteristics of the porous material. The dimensions of permeability are length squared (ft^2, cm^2, m^2, etc.). Permeability is the parameter preferred by the oil and gas industry where it is more practical for evaluating multi-phase fluid (oil, gas, water) flow.

Transmissivity – the rate at which groundwater moves through a unit width of the water-saturated portion of the aquifer, under a unit *hydraulic gradient* expressed in square feet per day (ft^2/day = ft/day x ft) or gallons per day, per foot (gpd/ft = gpd/ft^2 x ft). Transmissivity is equivalent to the *hydraulic conductivity* integrated over the thickness of an aquifer (x ft = aquifer thickness).

Specific capacity – the pumping discharge rate of a well divided by feet of *drawdown* of the water level in the well during pumping, commonly expressed in gallons per minute, per foot of *drawdown* (gpm/ft).

Specific yield – the drainable *porosity* of an *unconfined aquifer*, reported as a ratio of the volume of water that will drain under gravity, to the volume of saturated earth material. Specific yield is a dimensionless parameter that is commonly used to describe the proportion of *aquifer* material volume that provides water available for beneficial use. Compare specific yield to *porosity* and *effective porosity*: All three are dimensionless but multiplied by the volume of the saturated rock, *porosity* will equal total void space, *effective porosity* will return total groundwater volume, and specific yield will return the volume of available groundwater (**Sections 5.1.4**).

Storage coefficient – the volume of water released from or taken into storage per unit surface area of the aquifer, per unit change in *total head*. Like *specific yield*, storage coefficient is a dimensionless parameter—the numerator and denominator cancel. In an *unconfined aquifer*, the water released

from storage is from gravity drainage and the storage coefficient is essentially equivalent to *specific yield*. In a *confined aquifer*, water released from storage, also called *specific storage*, comes primarily from expansion of the water and compression of the *aquifer* as pressure is relieved during pumping. Because of the difference in mechanics of how water is released from storage, the storage coefficients of *unconfined aquifers* (0.1 to 0.3) are generally several orders of magnitude larger than those of *confined aquifers* (10^{-5} to 10^{-3}).

Specific retention – the ratio of the volume of water retained in the pores of an unconfined aquifer after gravity drainage to the total volume of earth material. *Specific retention* is a dimensionless parameter expressed as a percentage.

Well yield – the rate of groundwater discharged (pumped or flowing) from a well expressed in gallons per minute (gpm).

Artesian flow – occurs where the *potentiometric surface* of a *confined aquifer* is at a higher elevation than the top of the *aquifer*. Water in wells at these locations will rise above the top of the *aquifer* to the level of the *potentiometric surface*.

Gaining stream – a surface water stream or part of a stream, which receives *discharges* of groundwater from the underlying or adjacent *hydrogeologic unit*(s). Surface water flow attributed to groundwater is commonly referred to as *baseflow*.

Losing stream – a surface water stream or part of a stream, which *recharges* the underlying or adjacent *hydrogeologic unit*(s) resulting in decreased downstream flow.

Total dissolved solids (TDS) – a measure of the total concentration of minerals dissolved in groundwater, generally expressed in either milligrams per liter (mg/L) or parts per million (ppm). Generally mg/L is equivalent to ppm.

Geochemical water type – an expression of the dominant cations and anions dissolved in the groundwater.

5.1.2 Types of groundwater flow

Groundwater flow can be characterized as porous flow, conduit flow, fracture flow, or some combination of these three types:

- *Porous flow* occurs through open, interconnected, intergranular spaces (pores) within a sedimentary geologic unit (generally conglomerate, sandstone, siltstone, or unconsolidated deposits) or through intercrystalline pore spaces within igneous or metamorphic rocks. The size of the sediment grains or mineral crystals affects porous flow. Larger open pores between larger grains (or crystals) are generally more conducive to flow than smaller grains/pores. In an aquifer with a wide range of grain sizes (poorly sorted), the fine-grained material fills in the larger pore spaces and reduces flow toward that of a fine-grained aquifer. Porous flow is also referred to as *primary porosity,* i.e., the porosity that results from deposition of the sediments and subsequent diagenetic processes such as compaction and cementation of the rock matrix.

- *Conduit flow* occurs through large, discrete openings (pipes, cavities, channels, caverns, and other karstic zones), generally within relatively soluble sedimentary or evaporitic rocks such as limestone or dolomite, gypsum, anhydrite, or halite. Conduits form by the dissolution of soluble minerals in bedrock or by subsurface sediment transport (piping) through unconsolidated or loosely consolidated material.

- *Fracture flow* occurs through interconnected partings in bedrock: fractures and joints developed during structural deformation (folding, faulting), expansion (rapid overburden erosion) or compaction, (rapid deposition), physiochemical alteration (shrinkage during desiccation, bedrock weathering, soil formation) or thermal contraction

(fractured and columnar basalts). Fractures occur either along or across existing bedding planes or other types of geologic contacts. The *porosity* of conduits and fractures is referred to as *secondary porosity,* although, frequently, conduits and fractures within a unit can transport water several times faster than the primary porosity in many aquifers.

5.1.3 Groundwater recharge, discharge, and flow

Groundwater systems at all scales, from local unconfined aquifers to entire groundwater basins, are defined by the physical factors that determine recharge, storage, and flow through the system to discharge areas. **Figure 5-1** is a cross section that illustrates some of the concepts discussed in this and other sections of this study.

5.1.3.1 Groundwater recharge

The accumulation of groundwater within an aquifer requires a source of water and in shallow aquifers, that source is ultimately precipitation. Initially, precipitation will infiltrate at the ground surface, percolate through the unsaturated, or vadose, zone, and enter the water table. This process, alone, can take days to hundreds of years before the precipitation enters a receiving aquifer as "recharge." The path groundwater travels from there, however, can be complicated further by moving between aquifers and confining units depending on the flowpaths within a particular system. Understanding the sources, amount and delivery timing of recharge is essential to effectively characterize any groundwater resource. Despite its importance, recharge is one of the most difficult parameters to accurately quantify. Recharge cannot be measured directly, but is estimated indirectly using scientific tools such as chemical tracer, water budget, heat tracer, or groundwater level analyses (Healy and Scanlon, 2010).

In the relatively dry climate of Wyoming, the mountain ranges surrounding the basins receive high levels of precipitation (**Fig. 3-3**) and serve as significant sources of recharge. Consequently, the most important recharge areas in Wyoming are hydraulically connected with sources of mountain precipitation. The recharge that infiltrates alluvial materials and bedrock outcrops that border the mountain ranges (mountain front recharge), and the thick alluvial deposits underlying stream channels that receive a large proportion of their flows from mountain discharges is especially valuable. Recharge storage in Wyoming builds as snowpack accumulation during late fall, winter, and early spring when seasonal precipitation is higher and cool daily mean temperatures prevent melting. Recharge rates are highest in late spring and the earliest part of summer during and following snowmelt. During those times, vegetation is still in a quasi-dormant state, rates of evapotranspiration are relatively low, and soils are newly thawed. The melting snowpack maximizes contact with the ground surface and enhances the duration and rate of infiltration.

Conversely, the environmental conditions that exist in the semi-arid basin interiors limit the amount and delivery of recharge. There, evapotranspiration rates frequently exceed the low rates of precipitation. During most years, basin recharge events are limited to infrequent rainfalls, usually in the form of high intensity thunderstorms and springtime melting of the relatively thin prairie snowpack. The reduced permeabilities of basin soils, lower permeability and less efficient recharge across horizontal stratigraphic units, and the high efficiency with which semi-arid types of vegetation can utilize sporadic precipitation further restrict the amount of water available for recharge.

During a precipitation event, some of the moisture is intercepted by vegetation before it reaches the ground surface. This water, called canopy storage, is retained briefly and will later be lost to evaporation or fall to the ground. Precipitation that reaches the surface will infiltrate into the ground if the infiltration capacity of the soil has not been exceeded. Initially, infiltrating water will replace any depletion in soil moisture, and then the remaining infiltrating water will percolate downward under the force of gravity through the unsaturated zone to the water table. The hydraulic characteristics and antecedent moisture conditions
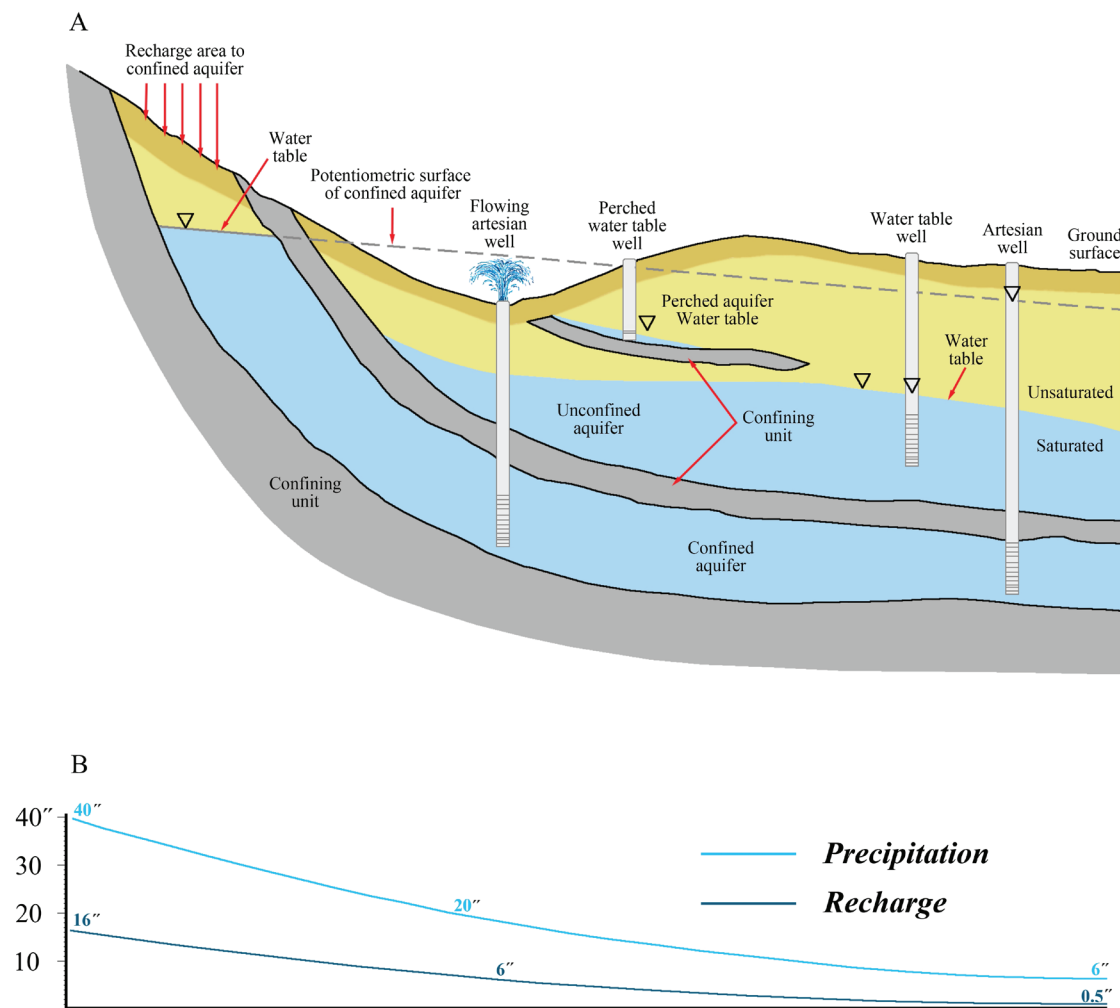
Figure 5-1. Conceptual cross-section of typical groundwater features that occur in Rocky Mountain structural basins and synclinal features of the Thrust Belt. Older hydrogeologic units outcrop and recharge at margins, dip steeply (basinward), and become confined within short distances. Potentiometric surfaces for unconfined aquifers are marked with inverted triangles (Δ)(water tables) and as a dashed line extending down-dip where the principal aquifer becomes confined. A perched aquifer has formed above a discontinuous confining unit. The figure shows water table wells completed in unconfined aquifers, and flowing and non-flowing artesian wells completed in the confined aquifer. B. Idealized recharge profile, in inches, basin margin to basin center. Adapted from WWC Engineering and others, 2007.

of the unsaturated zone affect the amount and speed of the infiltrating water that reaches the water table. If the infiltration capacity of the soil is exceeded, water flows overland to be stored on the surface in puddles (depression storage) or to discharge to streams. In the latter case, some of the overland flow may infiltrate the streambed and enter the receiving aquifer as recharge, downstream from the site of precipitation. A general assumption is that approximately 10 percent of precipitation recharges groundwater. The description given above is a general simplification of the infiltration process. It should be understood that infiltration rates can vary widely and are affected by multiple factors:

- Depth, composition, and hydraulic properties of the surficial materials (soil, bedrock and paving);
- Depth and degree of bedrock weathering;
- Antecedent soil moisture: was the soil dry, moist or wet before the event;
- Type, abundance, and density of vegetation;
- Extent, density, and proximity of root zones;
- Type, rate, and duration of precipitation;
- Evapotranspiration (ET) rates;
- Slope and aspect of the ground surface;
- Aperture, depth, interconnection, orientation, density, and exposure of bedrock fractures;
- Large openings, both natural (karst, animal burrows) and man-made (mines, pits, well-bores);
- Geospatial distribution, capacity, and permeability of surface depressions;
- Opportunity for recharge from surface waters;
- Local land use (irrigation, soil stripping, paved areas).

In addition to infiltration from the surface, an aquifer may also receive recharge as leakage from adjacent confining units. Although recharge may flow very slowly from confining unit to receiving aquifer, the volume of leakage can be quite substantial over time provided the geospatial contact area between the two units is large.

Artificial recharge from surface water diversion projects such as reservoirs, irrigation canals, and unlined pits, injection wells, and flow between aquifers in poorly completed wells may be significant in local areas of the Bear River Basin. The extent of artificial recharge is difficult to evaluate on a regional basis, but might be determined for small watersheds.

While several methods have been described for estimating recharge (Healy and Scanlon, 2010), direct measurement of recharge is problematic due to the high degree of geospatial and temporal variability of precipitation and the numerous factors that affect infiltration. In 1998, the Spatial Data and Visualization Center (SDVC) at the University of Wyoming conducted a statewide recharge evaluation using geospatial analysis. The SDVC published the results in the *Wyoming Ground Water Vulnerability Assessment Handbook* (Hamerlinck and Arneson, 1998). Originally, the SDVC calculated average annual recharge for the 1961 – 1990 period of record by:

- Compiling a map of soil-management-unit boundaries with assigned recharge fraction values (R/P = Average annual recharge/Average annual precipitation), as percentages of precipitation that reaches the uppermost aquifer in a given environment;
- Combining similar geologic units;
- Overlaying the average annual precipitation map and multiplying recharge fraction by precipitation to calculate average annual recharge.

Hamerlinck and Arneson (1998) observed several general relationships in the scientific literature on recharge:

- Recharge fraction (R/P):
  - Increases as the depth to the water table decreases.
  - Increases as precipitation increases.
  - Increases as the sand content of the soil increases.
  - Is higher in an above-average precipitation year and lower when precipitation is below average.

- Seasonal patterns and the timing of major events like spring snowmelt alter the fraction of mean annual precipitation that recharges groundwater.

This study used the SDVC approach (Hamerlinck and Arneson, 1998) to estimate average annual recharge in the Wyoming part of the Bear River Basin (**Chapter 6**) for the 30 year period of record from 1981- 2010. The analysis used two geospatial datasets: 1) percolation percentages for documented soil/vegetation combinations (**Fig. 6-5**) published in the Hamerlinck and Arneson (1998) study, and 2) average annual precipitation (**Fig. 3-3**) from 1981 through 2010 (PRISM, 2013). **Figure 5-2** shows average annual recharge for the 1981 – 2010 period of record; summary information is presented in **Tables 6-1 – 6-3**.

5.1.3.2 Groundwater discharge

Natural discharges of groundwater occur in many ways. In Wyoming basins, the most common modes of discharge include leakage between geologic units; flow from springs;, subsurface seepage (baseflow) into streams, wetlands, lakes, and other surface waters, and direct evaporation where the water table is shallow enough that capillarity or plant transpiration brings groundwater to the surface (evapotranspiration). Like recharge, the magnitude of total natural discharge is difficult to determine, especially on a basin-wide basis. While some forms of discharge, such as visible surface flows from springs, are readily measured, others are difficult to quantify because they are concealed (leakage between geologic units, subsurface flows in streambeds [hyporheic flows] or seepage into surface waters) or occur with wide variability over large areas (evapotranspiration). Discharges that cannot be measured directly must be estimated through proxy calculations. For example, using a mass balance (water balance) model can refine estimates when information on recharge and some discharges (e.g., surface water outflow, evapotranspiration) is available, as is the case in this study (**Chapter 8**).

In addition to withdrawals from wells, artificial avenues of groundwater discharge include seepage into mines and other excavations, discharges into irrigation and drainage canals, and flow between aquifers in poorly completed wells. Groundwater withdrawals for beneficial use are estimated in the previous water plan (WWDO, 2012) and are discussed in **Chapter 8**.

Groundwater discharge, buffered by the storage function of an aquifer, is generally more efficient than recharge. While recharge occurs intermittently by percolation through unsaturated materials, discharge is a more continuous process that occurs under more efficient saturated flow conditions. Under natural conditions, where there is no extraction of groundwater, recharge and discharge will reach a state of dynamic equilibrium over a time period that depends on precipitation, hydrogeologic characteristics, aquifer size, and the variability of the particular hydrologic inputs and outputs within the basin in question. Reasonable estimates of both recharge and discharge provide valuable baseline data to evaluate the sustainability of any groundwater development project.

5.1.3.3 Groundwater flow

Gravity drives groundwater flow. After water enters an aquifer in a recharge area it flows under saturated conditions to discharge areas controlled by the hydrogeologic characteristics of the aquifer. The rate of groundwater flow (as volume per unit of time) is determined by the hydraulic conductivity (the velocity with which water can move through the pore space), the cross-sectional area, and the gradient that prevails along the flow path. The time it takes for water to circulate through an aquifer can range from a few days in a shallow, permeable aquifer, to thousands of years in deeper aquifers. The arrangement of aquifers and confining units that store and convey groundwater constitutes the structural framework of the hydrogeologic system within a basin.

Although groundwater flow is driven by gravity, water does not always flow downward, but from areas of higher hydraulic pressure to areas of lower hydraulic pressure. In the deeper subsurface, groundwater can flow from a lower to a higher elevation, as observed at artesian wells (**Fig. 5-1**)

and some springs that discharge groundwater from deep aquifers. Groundwater will flow in the directions indicated on potentiometric surface maps if permeable pathways exist; however, flow along preferential pathways (e.g., fractures and faults) can depart from the direction of maximum gradient. Hydraulic gradients are commonly steep in low permeability geologic units where there is substantial resistance (friction) to flow. Conversely, high-permeability units, where friction is low, generally exhibit low hydraulic gradients. The slope (gradient) of a potentiometric surface within a highly permeable aquifer is somewhat analogous to a standing body of water, such as a pond where the resistance to flow in any direction is negligible and the gradient is virtually flat.

Groundwater flow rates through aquifers and confining units range from very high to very low, to essentially no-flow. The flow rate through the pores of a highly permeable aquifer of well-sorted gravel or through the large open conduits in a carbonate aquifer may be several feet per second (fps), whereas the flow rate within a clay-rich unit with very low, to essentially no permeability may be less than a few inches every 10,000 years. Hydraulic conductivity varies over 13 orders of magnitude in differing types of hydrogeologic units. Folding, fracturing, and faulting modify the permeability and other hydraulic properties of both aquifers and confining units, generally increasing permeability and decreasing the capacity of confining units to function as barriers to groundwater flow.

Groundwater occurs under unconfined (water table) conditions in unconsolidated deposits and bedrock formation outcrop areas throughout the Bear River Basin. In shallow, unconfined aquifers, recharge, flow, and discharge are predominantly controlled by topography, vegetation and stream drainage patterns. The water table of an unconfined aquifer is recharged by precipitation and generally reflects the overlying topography especially in areas of high relief. Groundwater from unconfined aquifers can discharge to the surface at springs where the elevation of the water table is greater than the surface elevation. Complex interactions can occur among bedrock aquifers, unconsolidated aquifers, and surface waters, especially along drainages lined with alluvial deposits. The discharge of groundwater to surface drainages contributes to base flow and in some cases constitutes all base flow.

Recharge of the deeper aquifers in the Bear River Basin occurs primarily in areas where they have been up-folded, eroded, and now crop out in the higher-elevation areas around the perimeter of the basin. These aquifers are unconfined at the outcrop areas, but as groundwater flows downdip from the recharge areas into the basin, it becomes confined by overlying low-permeability strata such as shale and claystone bounding the more permeable aquifers of sandstone, coal, fractured limestone and dolomite. Some recharge to deeper aquifers occurs as leakage from adjacent, usually underlying, hydrogeologic units. Groundwater discharges from confined aquifers to the surface can occur under several conditions. Contact springs discharge where recharge is rejected from fully saturated aquifers into headwater streams at the point where a streambed intersects the surface between a confining unit and an underlying aquifer. Springs also form where joints, fractures, or faults through a confining unit permit flow from an underlying aquifer to reach ground surface. Artesian wells will flow when the pressure head in the confined aquifer is higher than atmospheric pressure at land surface.

Confined groundwater flow within the deeper bedrock formations of the Bear River Basin is primarily controlled by structure and stratigraphy. Major aquifers and aquifer systems in the Bear River Basin occur predominantly within interstratified sequences of high- and low-permeability sedimentary strata. The aquifers are commonly heterogeneous and anisotropic on both local and regional scales. Deeper groundwater flow in the Bear River Basin is predominantly through permeable formations down-gradient from higher to lower hydraulic pressure. Where vertical permeable pathways exist, groundwater will follow them upward toward areas of lower hydraulic pressure.

5.1.4 Groundwater storage, safe yield, and sustainable development

In addition to functioning as the conveyance system for groundwater flow, the saturated geologic units that compose the aquifers of the Bear River Basin also store enormous volumes of groundwater. Understanding groundwater storage and how to develop groundwater resources in a particular area of interest without depleting storage and natural discharges to unacceptable levels are considered in most development projects. In this section, the basic technical concepts of groundwater storage and the environmental aspects of the "safe yield" concept are discussed. In fact, acceptable (or unacceptable) levels of depletion are frequently defined administratively by state law, court order, international treaty, or interstate agreements, such as the Amended Bear River Compact (**Appendix D**).

Two important aspects of groundwater resource assessments on any scale are the evaluation of both the total volume of groundwater present in an aquifer and the fraction of that volume that can be accessed, developed at an acceptable cost, and used beneficially. Technical, financial, and legal factors determine what fraction of the total volume of groundwater stored within a particular aquifer can be considered an available resource. Initially, development costs, water rights considerations, and water quality requirements are three primary factors that are evaluated to determine what part of the groundwater contained within an aquifer will be producible. The depth to the resource and other physical, cultural, legal, and institutional constraints of the project under consideration may limit accessibility and preclude the development of a particular groundwater resource due to associated costs or technical limitations. Groundwater must be of suitable quality to satisfy the requirements for its intended use. Groundwater quality is addressed in **Section 5.5** and **Chapter 7**.

The amount of water that an aquifer will yield to natural drainage or to pumping is determined by its hydraulic properties, which are directly or indirectly dependent on an aquifer's effective porosity **(Section 5.1.1)**. Important hydraulic properties with respect to the sustainable development of groundwater resources are related to the storage coefficient of the material that composes an aquifer, particularly specific yield (for unconfined aquifers) and specific storage (for confined units).

5.1.4.1 Groundwater storage

The concept of storage coefficient can be applied to both unconfined and confined aquifers. The storage coefficient is the amount of water that a unit volume of an aquifer will release from (or take into) storage per unit change in hydraulic head, expressed as a percentage or decimal fraction.

Specific yield applies only to unconfined aquifers; it is the fraction of water that a saturated unit volume of rock will yield by gravity drainage. Specific yield is expressed as a percent (or decimal fraction) of the unit volume. In an unconfined aquifer, specific yield is essentially the same as effective porosity. Specific retention, also expressed as a percent (or decimal fraction) of the unit volume, is the volume of water that remains in the unit volume of rock after drainage, in isolated pores and attached to the aquifer matrix by molecular attraction and surface tension (capillarity). Because capillarity is higher in fine-grained materials (with smaller pore size and proportionately greater pore-surface area), it follows that finer-grained aquifers in general have higher specific retentions than coarser-grained aquifers even though finer-grained materials may have higher total porosity than coarser-grained materials. For example, a larger fraction of the total water would be retained after drainage in a cubic foot of fine sand than in a cubic foot of river cobbles. The sum of specific retention and specific yield is equal to porosity. Highly productive unconfined aquifers are characterized by high specific yields.

The mechanisms of releasing groundwater from unconfined and confined aquifers are very different. In an unconfined aquifer, water is simply drained by gravity and hydraulic head is lowered. In a confined aquifer, water released from storage comes from the expansion of groundwater and the compression of the rock matrix as water pressure is reduced by pumping or artesian discharge.

This is called the specific storage. Because the volume of water that is produced due to these elastic properties (specific storage) is negligible in an unconfined aquifer, the storage coefficient in an unconfined aquifer is essentially equal to specific yield. Conversely, specific yield cannot be determined for a confined aquifer unless the water level (hydraulic head) is reduced to the point that the aquifer becomes unconfined, after which the storage coefficient is essentially equal to the specific yield.

To some extent, the groundwater stored in an aquifer can operate as a buffer between recharge, natural discharge and withdrawals, allowing relatively constant production of groundwater during periods of variable recharge. Enormous volumes of water can be released from storage in a geospatially large aquifer from relatively small persistent declines in hydraulic head, allowing continual withdrawal through periods of deficient recharge. Large declines in hydraulic head from over pumping, however, can reduce aquifer water levels to the point where recharge is induced, turning gaining streams into losing streams or drying up spring flows. Because of the difference in how water is released from storage, specific yields in unconfined aquifers are generally orders of magnitude larger than the specific storage of confined aquifers. Thus, unconfined aquifers yield substantially more water per unit decline in hydraulic head over a much smaller area than do confined aquifers. Unconfined aquifers are therefore generally more attractive prospects for development. Properly managed, groundwater is one of society's most important renewable resources; however, over-pumping can result in a long-term and perhaps irreversible loss of sustainability through storage depletion and compression of the aquifer material.

5.1.4.2 Safe yield

The term "safe yield" is used to describe the rate of groundwater production that can be sustained without causing an unacceptable level of depletion of storage volume or other adversities, such as degradation of groundwater quality or depletion of surface water flows. In the past, safe yield

estimates were tied to average annual recharge rates and were thought to predict aquifer responses to long-term withdrawals and recharge inflows. Safe yield estimates have been applied over a wide range of scale, from individual wells to entire structural or drainage basins. The concept of safe yield originated in the early twentieth century with engineering studies of surface water reservoirs.

The concept was subsequently applied to groundwater resources. Lee (1915), in his article, *The Determination of Safe Yield of Underground Reservoirs of the Closed Basin Type* first described safe yield as, "the limit to quantity of water that can be withdrawn regularly and permanently without dangerous depletion of the storage reserve." Lee noted that safe yield… "is less than indicated by the rate of recharge, the quantity depending on the extent to which soil evaporation and transpiration can be eliminated from the region of groundwater outlet." Meinzer (1923) placed it within the context of economics when he defined safe yield as ". . . the rate at which ground water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible." However, it is now recognized that ownership; legal, financial and environmental issues; the potential for aquifer damage, and interference with the development of other resources must also be considered in evaluating "safe yield" for groundwater development. The definition given by Fetter (2001) includes these factors,

> "The amount of naturally occurring groundwater that can be economically and legally withdrawn from an aquifer on a sustained basis without impairing the native groundwater quality or creating an undesirable effect such as environmental damage. It cannot exceed the increase in recharge or leakage from adjacent strata plus the reduction in discharge, which is due to the decline in head by pumping."

Two notable misconceptions that arose in early discussions of the safe yield concept persist to this day. The first is that groundwater withdrawals from wells and springs are sustainable as long as

they do not exceed the amount of annual recharge in a particular area. A second, persistent belief follows from the first: developing a water budget will determine a "safe" amount of groundwater development.

Theis (1940) concisely addressed the misconception relating safe yield to annual recharge levels by identifying the sources of water for groundwater development,

> "….under natural conditions……previous to development by wells, aquifers are in a state of approximate dynamic equilibrium. Discharge by wells is thus a new discharge superimposed upon a previously stable system and it must be balanced by an increase in the recharge of the aquifer, or by a decrease in the old natural discharge or by loss of storage or by a combination of these."

The scientific literature has continually supported Theis' observations since then. In brief, the amounts of groundwater withdrawn by new development projects initially come from storage depletions and then gradually transition to induced recharge of surface water (stream flow depletions). In the best case, the newly developed groundwater system will reach a new state of dynamic equilibrium over time but this includes, by necessity, depletions of streamflow or groundwater storage or both. Thorough explanations of these concepts can be found in Sophocleous (1998) and Barlow and Leake (2012).

In the past, when it was thought that the upper limit of an aquifer's safe yield was determined by the amount of annual recharge, the sustainability of groundwater development was frequently analyzed by a conservation of mass approach variously referred to as a water balance, hydrologic budget, or water budget. The fundamental expression for this type of analysis as applied to groundwater resources is:

Recharge – Discharge = Change in Storage
(measured over the same time period)

By application of this equation, recharge rates could be estimated by making reasonable estimates of natural discharges and groundwater withdrawals from wells if it is assumed that there was to be no change in storage. The recharge estimates were then used to determine the upper limit of an aquifer's safe yield.

Average annual recharge rates for the Bear River Basin estimated by the SDVC (Hamerlinck and Arneson, 1998), are presented in **Figure 5-2**. Based on the SDVC evaluation, annual recharge to specific groups of aquifers is estimated and discussed in **Section 6.2**. A water balance for the Bear River Basin was prepared for this study (**Chapter 8**) using information provided in the previous Bear River Basin Water Plan (WWDO, 2012) and additional information developed by the WSGS. The aquifer-specific recharge estimates contained in **Chapter 6** of this study were integrated into the water balance which should be used to:

- Provide a comparison of estimated groundwater withdrawals to estimated levels of natural discharge and recharge;
- Emphasize the mass balance aspect of water resources that is, "water in" (recharge) equals "water out" (natural discharges and artificial withdrawals);
- Develop further understanding of the groundwater/surface water system of the basin;
- Stimulate discussion among stakeholders of what constitutes sustainable yield (**Section 5.1.4.3**) in the Bear River Basin.

Practically, it is unlikely that a unique and constant value of safe yield can be calculated accurately on the basin scale because of a number of limiting physical and temporal factors.

Drainage basins cannot be treated as homogeneous underground reservoirs but are complex systems of aquifers and confining units that possess, instead, high levels of geological and hydrological heterogeneity. For example, a large drainage basin such as the Platte River (Taucher and others, 2013), may contain several structural basins, wholly or in part. Because of these complexities, the understanding of key factors such as basin

geometry and structure, hydraulic relationships between basin hydrogeological units, and deep basin hydrodynamics is largely absent within a regional safe yield model.

Aspect(s) of spatial scale must be considered. An analysis of total groundwater uses over a regional scale, such as a river basin, may indicate that groundwater withdrawals constitute a small percentage of calculated annual recharge and imply that water resources are not over-utilized. A regional analysis may, however, conceal local scale groundwater storage depletions that have become problematic. Again, in the case of the Platte River Basin (Taucher and others, 2013), a basin-wide water balance determined that recent annual consumptive uses of groundwater constitute about 13 percent of mean annual recharge. From this analysis, a safe yield evaluation would conclude that groundwater storage levels in the basin are relatively secure. In fact; some areas of the High Plains aquifer in Laramie County have seen maximum water level declines of 25-50 feet since 1950 (McGuire, 2013).

Sufficient datasets required to make such estimations have not been obtained in most drainage basins for a number of reasons. First is the expense of collecting adequate hydrogeologic data from an acceptably sized sample set. The problem is further exacerbated in lightly populated rural areas where groundwater wells are sparsely distributed. There, adjacent sampling points (wells) are frequently separated by miles of unpaved roads, inaccessible during winter and early spring months. Second, wells are most likely sited in hydrogeologic units where the probability of successful completion is highest. Thus the available hydrogeologic data is skewed toward over-represented productive areas and away from less productive units where few wells are drilled. For example, 65 percent of likely producing wells of all types are sited in Quaternary alluvial units which comprise 20 percent of basin surface area (**Table 6-3**). The remaining wells (35 percent) are sited in bedrock aquifers (**Figs. 8-1** through **8-4**).

Hydrologic inputs (recharge) and outputs (discharges) are not delivered instantaneously and,

in most cases, have not been accurately measured. Similarly, changes in storage are dependent on aquifer response times that can range from days to hundreds of years Sophocleous (2005). Thus, currently observed changes in storage may reflect present day discharges superimposed on recharge levels from decades past. In such cases, water managers must be careful to avoid evaluating current aquifer storage volumes relative to recent precipitation rates given the long lag times of some aquifers and the cyclic nature of drought in the semi-arid west.

5.1.4.3 Sustainable development

The concept of sustainable development has received increasing attention in the international water resources community since it first appeared in the early 1980s. The World Commission on Environment and Development defined sustainable development as, "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs." In the U.S., sustainable development of water resources continues to grow in importance in light of USGS studies documenting widespread groundwater storage declines in the U.S. (Konikow, 2013; Bartolino and Cunningham, 2003) and the related effects of surface water depletion and land subsidence (Galloway and Burbey, 2011), most notably in the arid and semi-arid western states.

The American Society of Civil Engineers (ASCE, 1998) define sustainable water systems as, "… those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity." The list of factors that affect the planning and development objectives of any water resource system is extensive. Water planners are required to consider current and future water demands, population, land use, climate, public opinion, water resource utilization, technology, and hydrologic science. Given the uncertainties encountered in these analyses, it is likely that no constant single value of sustainable yield can be developed for a particular project. The determination of sustainable yield is not a single set of calculations but a process that will require
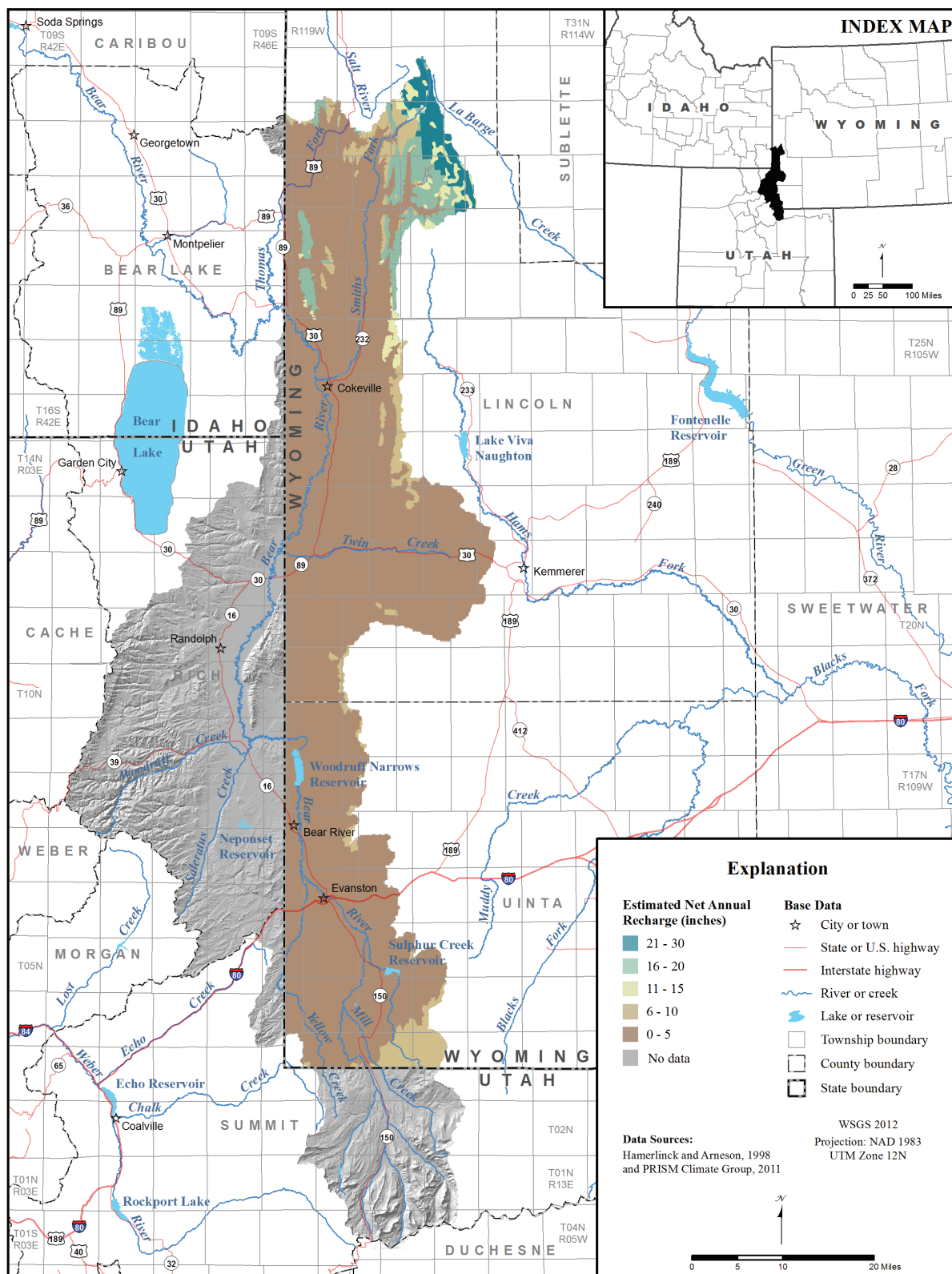
Figure 5-2. Estimated net annual aquifer recharge, in inches, Bear River Basin, Wyoming.

periodic reevaluation as the design elements change with time (Maimone, 2004).

Mandel and Shiftan (1981) proposed a six step procedure1 for estimating the sustainable yield of an aquifer:

1. Determine mean annual recharge.
2. Identify the first unacceptable affect that will occur as water levels are lowered. This may be defined as a physical constraint (depletion of measured springflow), or a violation of government regulations (infringement on senior water rights, mandated in-stream flows, or provisions of an interstate compact).
3. Define the quantitative relationship between water levels and the timing and extent of the unacceptable affect previously identified. This step may use widely known mathematical functions or the development of groundwater models that apply over wide areas of the aquifer or to a few critical locations only.
4. Determine minimal acceptable water levels for the aquifer or for the critical areas of interest.
5. Calculate the rate of natural discharge that will result when a new state of dynamic equilibrium consistent with the minimal water levels is established.
6. The sustained yield is the difference between Steps 1 and 5.
   Modified from Sophocleous (1998)

To this, a seventh step might be added, *"Review and reevaluate yield estimates as water demands, population, land use, climate, public opinion, water resource utilization, technology, hydrologic understanding of the system, and available alternate water sources change with time."*

The concept of sustainable development recognizes the ultimate sources of groundwater withdrawals defines the first unacceptable effect(s) of storage and surface flow depletions, establishes minimal water levels that ensue from those depletions and calculates the rate of diminished natural discharge. Still, if integrated into any groundwater development program, the results of sustainable

yield calculations must be supported by a long term monitoring plan that utilizes an adaptive management approach. Barlow and Leake (2012) discuss, in depth, the challenges of designing, conducting, and analyzing the results of a streamflow depletion monitoring program.

5.2 Map/rock units: geologic, stratigraphic, and hydrogeologic

The geologic framework for the Available Groundwater Determination, Technical Memorandum for the Bear River Basin is the assemblage of rocks and other geologic elements that compose the groundwater basins, their hydrologic properties, and the stratigraphic and structural interrelationships that provide the plumbing system for the recharge, storage, and flow of groundwater. Geologic units and rock units are distinct mappable units (described in **Appendix A** and discussed further in **Chapter 7**) that have been defined and described in the geologic nomenclature. They are classified in descending order of magnitude as supergroups, groups, formations, members, beds, tongues, and flows.

The North American Stratigraphic Code (2005) establishes the basis for the definition, classification, and naming (nomenclature) of distinct and mappable bodies of rock. These bodies are referred to as geologic units and rock units. While the code does not clearly distinguish between the two, rock units are commonly considered equivalent to lithostratigraphic units, defined by mappability, stratigraphic position, and lithologic consistency. Geologic units are distinguished over a wider range of properties, such as lithology, petrography, and paleontology, and can include lithostratigraphic (lithodemic for non-layered intrusive and metamorphic rocks), biostratigraphic, chronostratigraphic, geochronologic, and other less familiar stratigraphic units. Stratigraphic units are generally layered or tabular and established on the basis of any or several of the properties that distinguish them from adjacent geologic units.

The USGS Geologic Map of Wyoming (Love and Christiansen, 1985) provides the most

comprehensive and up-to-date map of surface geology readily available and relevant for this study. The map delineates the surface outcrops of distinguishable bodies of "rocks" as "map units." The explanation sheet (Sheet II) of the Geologic Map of Wyoming describes where certain map/rock units that consist of one or more stratigraphic units have been combined on the map because of cartographic limitations. The explanation also describes the chronologic and geographic correlations between stratigraphic and map units, as well as the geographic and chronological distribution of both the map units and their component stratigraphic units. The WSGS "Stratigraphic Chart Showing Phanerozoic Nomenclature for the State of Wyoming" (Love and others, 1993) correlates the stratigraphic units shown on the 1985 map explanation developed from the individual 1° x 2° (1:250,000 scale) geologic quadrangle maps covering the state, and includes revisions subsequent to the 1985 map. Because the map/rock units of the Geologic Map of Wyoming may consist of more strictly defined stratigraphic units (primarily lithostratigraphic units), they are considered to be geologic units. The USGS and the WSGS compiled the map/rock units presented in the 1985 Geologic Map of Wyoming into a digital database of GIS geologic units which was used in the development of **Plate 1** (surface geology), **Plate 2** (surface hydrogeology) and the hydrostratigraphic chart contained in **Plate 5**.

The Bear River Basin GIS geologic units mapped on **Plate 1** are described in **Appendix A**. Throughout this study, bodies of rock are described in terms of rock (lithostratigraphic) units where the more restrictive distinction is applicable (primarily in **Chapter 7**) and as geologic units where a more inclusive definition is appropriate. **Plate 2** maps the exposures of the hydrogeologic units in the Bear River Basin. Hydrogeologic units can be composed of multiple, or portions of geologic and/or rock units. The units that compose an aquifer or aquifer system in one area may be considered differently in another area where the same units have different hydrologic properties or are composed of different geologic units. The hydraulic, physical, and hydrogeochemical characteristics of individual

hydrogeologic units (aquifers and confining units) established on the hydrostratigraphic chart are discussed in detail in **Chapter 7** regarding their component geologic or lithostratigraphic units.

Plate 5 provides hydrostratigraphic information from previous studies so that informed readers can track the historical development of the basin's hydrostratigraphy. The hydrostratigraphic chart is based on stratigraphic units, several of which are not distinguished within the GIS geologic units used to develop **Plate 2**. In addition, GIS geologic units used to map specific hydrogeologic units comprise different stratigraphic units in different areas in the Bear River Basin. This limitation precluded designating some GIS units as a specific aquifer or confining unit. In cases where specific designations could not be made (some Mesozoic and Paleozoic units), the hydrogeologic units on **Plate 2** are categorized as undifferentiated.

Most geologic maps are now developed using computers. Computerization allows great flexibility in how geologic data can be organized, presented, and updated. The value of this technology is reflected in this Technical Memorandum and the other studies that compose the State Water Plan. Map data has been made available to the public in formats that allow a skilled viewer to access, download and process geospatial data, and work directly with maps and Figures present within this and other reports. Computerization greatly facilitated the process of organizing the GIS geologic units into hydrogeologic units and the development of the surface hydrogeology map and associated hydrostratigraphic chart provided as **Plate 2**. **Plate 2** maps Bear River Basin surface hydrogeology and is used throughout this study as a basis for presenting the data compiled for water wells, springs, potential contaminant sources, and potential groundwater development areas. As discussed in **Sections 5.1.3.1** and **6.2**, the GIS-based surface hydrogeology map also allowed a reasonable quantitative estimate of annual recharge to the outcrop areas of aquifers exposed in the Bear River Basin.

5.3 Wyoming statewide aquifer classification system

The 2007 Wyoming Statewide Framework Water Plan (WWC Engineering, Inc. and others, 2007) proposed a generalized aquifer classification system for the entire state based on the amounts of water a hydrogeologic unit has historically provided for beneficial use. Individual geologic units are assigned to one of seven categories by evaluation of their hydrogeologic characteristics. The statewide classification system distinguishes the following seven hydrogeologic categories:

Major aquifer - alluvial: The highly permeable, unconsolidated, flat-lying sand and gravel deposits that compose the alluvium located along rivers and streams are some of the most productive aquifers in the state and the Bear River Basin. Under favorable conditions these aquifers can provide well yields of 500-2,000 gallons per minute (gpm). Yields are generally lower where the deposits are either thin, contain abundant fine-grained material, located at higher elevations or hydrologically isolated from active streams (e.g., terrace deposits). Flow through unconsolidated material occurs through primary (intergranular) porosity. Where the alluvial aquifer is hydraulically connected with an active stream, direct infiltration from the stream provides most of the groundwater in storage, and alluvial-aquifer water quality reflects the water quality of the stream, with modification by the mineral composition of the aquifer matrix. Where discharge from shallow bedrock aquifers is a primary source of alluvial-aquifer recharge, surface water quality is similarly influenced.

Major aquifer - sandstone: Consolidated bedrock formations, composed primarily of permeable coarser-grained lithologies, such as sandstone and conglomerate, commonly supply useable quantities of groundwater. In some cases, sandstone aquifers yield large quantities of good quality groundwater. Most of the groundwater stored in these aquifers is held in the sandstones' primary porosity. Porous flow is generally dominant; however, fracture flow can be significant in structurally deformed areas. Within the interior valleys, the sandstone aquifers are mostly horizontal and some are widespread.

Relatively thick sandstone sequences that compose the Tertiary Wasatch aquifer system and the Mesozoic Nugget aquifer are the most productive sandstone aquifers in the Bear River Basin. Older Mesozoic sandstone aquifers exposed by erosion along the ridges and flanks of the Bear River Basin highlands commonly dip to the west (**Pls. 1** and **2**) and may contain accessible groundwater resources for several miles downdip of the outcrop areas. Groundwater quality tends to decrease with increasing depth. Some sandstone aquifers may exhibit poor yields due to local heterogeneity, high content of fine-grained material, cementation, and lack of fractures. Layers and lenses of sandstone (and coarser lithologies) are generally the most productive intervals. Where sandstone layers are not thick and widespread but rather heterogeneous and discontinuous, wells must penetrate several individual water-bearing strata to provide adequate flow for the intended use.

Major aquifer – limestone: Carbonate formations are composed primarily of Paleozoic and lower Mesozoic limestone or dolomite that occur throughout Wyoming and are present in all seven major river basins. Wells production rates are highly variable in limestone aquifers. Localized areas of vigorous groundwater flow and high productivity are present where enhanced secondary permeability has developed along solution-enlarged fractures caused by structural deformation and groundwater circulation. In the Bear River Basin, these aquifers are exposed primarily along the ridges and flanks (**Pl. 2**) of highlands where the upthrown sides of thrust faults have been eroded away to expose carbonate formations. The potential for vigorous recharge and groundwater circulation in Paleozoic carbonate aquifers is highest in outcrops located along the west flank of the southern Tunp Range (Tunp Fault), Crawford Mountain (Crawford Fault), and the northern foothills of the High Uintas (North Flank Fault). In Wyoming, examples of major limestone aquifers include the Madison, Wells, Darby and Bighorn formations. Depending on the degree of enhanced permeability, the major limestone aquifers can host accessible groundwater resources for several miles downdip of their outcrop areas. However, they generally are more deeply buried than the overlying

sandstone aquifers and access to them becomes progressively difficult as burial depths increase.

Minor aquifer: These consolidated bedrock formations commonly provide groundwater for local use from relatively low-yielding wells (generally 50 gpm or less). Water quality in the minor aquifers varies from good to poor. The minor aquifers are typically thinner, more heterogeneous, have lower yields, and are less laterally extensive than the major aquifers. Similar to other aquifer types, outcrop areas are characterized by generally better circulation and groundwater quality, both of which deteriorate, in many cases, rapidly with depth.

Marginal aquifer: These consolidated bedrock formations host mostly low-yielding wells (1-5 gpm) that may be suitable for domestic or stock use. Sandstone beds are the primary source of groundwater in marginal aquifers, although fractured fine-grained strata and coal seams yield water locally. Marginal aquifers rarely yield substantial quantities of groundwater, and then only under favorable local conditions. The permeability of marginal aquifers is generally low enough that in some areas they also function as minor (leaky) confining units.

Major confining unit: These consolidated bedrock formations are composed primarily of thick layers of marine shale that hydraulically separate underlying and overlying aquifers on a regional scale. These confining shales are some of thickest and most widespread formations in Wyoming. Because of their high clay content, these strata are generally less brittle than other lithologies and therefore less subject to fracturing that could enhance permeability. These units typically yield little or no groundwater, and the groundwater that is produced is commonly of poor quality. Occasionally, wells completed in isolated zones of confining units produce small quantities of useable groundwater. The crystalline Precambrian rocks that underlie the basins and crop out in the surrounding mountain ranges form the basal confining unit and the lower limit of groundwater circulation. In and near the upland outcrop areas, these rocks possess enough fracture permeability

to sustain springs and low-yield wells that provide good-quality groundwater.

Unclassified: These geologic units are of small extent and lack adequate data for hydrogeologic classification.

The Wyoming Statewide Framework Water Plan (WWC Engineering, Inc. and others, 2007; Figure 4-9) classified the Bear River Basin geologic units; the more common names used in the framework water plan for time equivalent stratigraphic units (**Pl. 5**) are noted in parentheses:

Major Aquifer - Alluvial
>   Quaternary alluvium

Major Aquifer – Sandstone
>   Wasatch Formation
>   Fowkes Formation
>   Mesaverde and related rocks
>   Nugget Sandstone
>   Gannett Group (time equivalent, Cloverly/ Dakota Formations)

Major Aquifer - Limestone
>   Wells Formation (time equivalent; Tensleep Sandstone, Minnelusa Formation)
>   Madison Group and Bighorn Dolomite Flathead Sandstone

Minor Aquifer
>   Quaternary non-alluvial deposits
>   Twin Creek and Thaynes limestones
>   Evanston Formation
>   Frontier Formation
>   Phosphoria Formation and related rocks

Marginal Aquifer
>   Woodside Shale and Dinwoody Formation

Major Aquitard (Confining Unit)
>   Hilliard Shale (time equivalents: Cody Shale, Niobrara Formation, Steele Shale, Baxter Shale)
>   Bear River Formation, Sage Junction Formation, Thomas Fork Formation,

Aspen Shale (time equivalents: Mowry
Shale, Thermopolis Shale)
Precambrian rocks

While the 2007 Wyoming Statewide Framework aquifer classification system provides a general summary of the groundwater resources of the seven major drainage basins of Wyoming, the updated individual river basin plans provide a greater level of hydrogeologic detail and analysis. **Plate 2** summarizes the hydrogeology developed by this study for the Bear River Basin. Correlations between the 2007 Wyoming Statewide Framework Water Plan aquifer classification system (WWC Engineering, Inc. and others, 2007), and the hydrogeology presented in this study are explained on **Plate 5.**

5.4 Groundwater circulation in the Bear River Basin

Complex Thrust Belt structures (Ahern and others, 1981), principally thrust, reverse, and normal faults, and fracture zones, coupled with topography, control groundwater circulation in the Bear River Basin (**Chapter 4; Pl. 1; Figs. 4-1 through 4-6**). Ahern and others (1981) discussed groundwater circulation by dividing Thrust Belt aquifers into three groups: 1) heavily fractured formations that pre-date the Upper Cretaceous deposition of the Hilliard Shale, 2) post-Hilliard Cretaceous and Tertiary units, and 3) Quaternary aquifers. This section contains a discussion of groundwater circulation in these aquifer types and an overview of the influence faults and fractures have on groundwater circulation.

5.4.1 Groundwater circulation in Quaternary aquifers (Ahern and others, 1981)

In terms of the volume of water withdrawn and the number of wells permitted, the most widely used aquifer system in the Bear River Basin is the Quaternary alluvial aquifer that lies along the Bear River and its tributaries (WWDO, 2012). Nearly all of the basin's irrigation wells (**Fig. 8-1**), as well as most of the wells permitted for livestock (**Fig. 8-2**), municipal (**Fig. 8-3**), and domestic (**Fig. 8-4**)

uses are located within the Quaternary system. Ahern and others (1981) report that the alluvial aquifer system is recharged primarily by direct infiltration of precipitation, discharge from bedrock aquifers, recharge from irrigation and infiltration of streamflows in losing reaches of headwater streams. Evapotranspiration, groundwater discharges into surface water flows, and withdrawals from wells constitute the principal forms of aquifer discharge. Groundwater flows within this system generally follow the topography of the watershed drainages, that is, toward or parallel to the channels of the Bear River and its tributary streams (Glover, 1990).

5.4.2 Groundwater circulation in post-Hilliard aquifers (Ahern and others, 1981)

The Upper Cretaceous and Tertiary aquifers that formed after the deposition of the Hilliard Shale (89 – 84 Ma), constitute the most areally extensive bedrock aquifer exposures in the Bear River Basin, most notably in the southern half of the basin. The post-Hilliard group is extensively utilized and includes the Salt Lake, Fowkes, Wasatch, Evanston and Adeville aquifers. Recharge to these aquifers consists of infiltration of rainfall and snowmelt and streamflow seepage in ephemeral streambed reaches. Natural discharge occurs primarily at gravity driven springs and seeps (**Pl. 3**) and as direct flows into alluvial sediments. Ahern and others, (1981) note that groundwater circulation in these aquifers is primarily controlled by local topography and that artesian discharge is common only along stream drainages.

5.4.3 Groundwater circulation in pre-Hilliard aquifers (Ahern and others, 1981)

Ahern and others, (1981) noted that groundwater circulation in the highly fractured pre-Hilliard aquifers is heavily controlled by faults and fracture sets. Structural control of groundwater circulation is especially marked in the northern half of the Bear River Basin where numerous north-south parallel systems of reverse and normal faults (**Pl. 1**) typically lie in relatively close proximity to one another. The close positioning of several large

adjacent faults is apparent in Cross Section B-B' (**Figs. 4-1** and **4-3**) that transects almost the entire width of the basin in Wyoming, from two and a half miles west of Cokeville extending eastward into the Green River Basin. In the ten and a half-mile distance the cross section covers from its western end to the Tunp Thrust Fault, the cross section encounters five normal faults, two thrust faults and one high angle reverse fault at land's surface. The frequency of faulting is even higher in the 21 mile long transect that comprises the Bear River Basin portion of Section C-C' (**Figs. 4-1** and **4-4**). Pre-Hilliard aquifers outcrop with greater frequency north of Section C-C' while post-Hilliard exposures dominate to the south.

5.4.4 Influence of Thrust Belt structure on groundwater circulation

The Thrust Belt fault and fracture zones in the late Mesozoic and Paleozoic aquifers of the Bear River Basin control groundwater circulation by acting as hydraulic barriers or conduits for groundwater flow in the geologic units they intersect. The effects that a particular fault or fracture set exerts on groundwater flow can be complex. Numerous physical characteristics of the fault or fracture set, such as its type, spatial extent, deformation type and history, aperture (size of its openings), fluid chemistry and reactions, and orientation, can change the direction and magnitude of groundwater flows. Other factors that can modify groundwater circulation include the geospatial, hydraulic, and lithologic properties of the rock units that the fault transects and also the fault's proximity, hydraulic connectivity, and spatial relationship to other faults and fracture sets.

Faults most often act as barriers that impede the flow of groundwater across strike in two ways. First, relatively impermeable rocks can be juxtaposed with more permeable units in the adjacent fault wall by the vertical displacement of stratigraphic units. Second, during the formation of the fault, friction between moving fault walls can grind rocks into clay-like, fine-grained, low-permeability sediments. These deposits, called fault gouge, fill in the spaces between the adjacent fault walls forming a fault core that impedes the flow of groundwater. In either case, the flow of groundwater can be redirected either horizontally, along the strike of the fault, or vertically depending on the hydraulic pressure gradients of the surrounding aquifers and confining layers. Many of the springs in the Bear River Basin occur along normal faults where horizontal groundwater flow has been disrupted and redirected upward to the surface under artesian conditions (**Fig. 5-1; Plate 3**).

The presence of a fault can also increase the flow of groundwater especially in the damage zones that flank the fault's core. The small faults, fractures, veins, and folds that typically form the damage zones may extend for hundreds of feet on either side of a large fault and can act as groundwater conduits that have hydraulic conductivities which are several orders of magnitude higher than the surrounding host rock. If the damage zones are hydraulically connected to a network of other faults, they can convey water to springs and wells from areas that cover several square miles. The hydrogeologic heterogeneity created by faults can make it difficult to accurately determine the dominant patterns of groundwater circulation in heavily faulted regions, even in areas where numerous monitoring wells exist. This difficulty is exacerbated in many parts of the Bear River Basin where bedrock wells are sparse. Thus, groundwater patterns are not well understood in those areas.

5.5 Natural groundwater quality and hydrogeochemistry

The practical availability of a groundwater resource depends on a combination of hydrologic, technical, legal, institutional, and cultural factors. The feasibility of development and potential uses for a groundwater resource are primarily dependent on water quality. For this study, the USGS compiled groundwater quality data for the Bear River Basin hydrogeologic units (**Section 5.6**) from several sources. These data confirm that the best quality groundwater is generally found in regions that are closest to recharge areas, and that quality is affected by chemical reactions that occur during infiltration through the vadose zone and circulating through or residing in the aquifer.

Factors that affect groundwater quality include the types and density of vegetation in recharge areas, and the mineral composition, grain size, transmissivity, rate of circulation, and temperature of the vadose zone and aquifer matrix. This generalization is more applicable to the "minor" and "marginal" aquifers of the Bear River Basin than to the "major aquifers," within which groundwater circulation is relatively (often substantially) more vigorous. Groundwater quality in the Bear River Basin varies from fresh, with total dissolved solids (TDS) less than 500 mg/l (ppm), suitable for any domestic purpose, to deep and briny oil field aquifers unsuitable for virtually any use, with TDS greater than 300,000 mg/L.

In the absence of irrigation, most alluvial aquifers receive recharge from hydrologically connected streams and underlying or adjacent bedrock. Irrigation can dominate recharge when application is active. Direct precipitation can also add to recharge, but due to high evapotranspiration rates in the interior lowlands, the amount of precipitation that reaches the water table is diminished, sometimes severely. Where recharge from streams dominates, groundwater quality is generally good. Sand, gravel, and other unconsolidated aquifer materials filter sediment, bacteria, and some contaminants from surface waters, producing water that is clear and with a chemical composition that reflects the composition of the source waters. Where bedrock recharge sources dominate alluvial groundwater quality reflects that of the surrounding formations in proportion to their contribution, commonly at a higher TDS concentration than recharge from surface waters. Irrigation water also affects groundwater quality in proportion to its TDS composition. In addition, irrigation water applied to permeable soil that has not been naturally saturated for millennia will dissolve, mobilize, and concentrate soluble minerals, primarily salts. Irrigation return flows can degrade water quality in streams.

Bedrock aquifers receive recharge through the infiltration of precipitation, by discharge from adjacent bedrock and alluvial formations, and from surface waters, including irrigation. In

general, recharge is dominated by precipitation in outcrop areas where there is no natural surface water or irrigation. Recharge from surface water is prevalent along streams and associated saturated alluvial deposits; however, groundwater discharge from bedrock to streams that support baseflow is also common throughout the Bear River Basin. Recharge of bedrock aquifers from streams is generally restricted to periods of very high flow and flooding. Groundwater developed in bedrock aquifers close to recharge areas or at shallow depth may be of high quality, regardless of the host geologic unit. As water flows deeper into the basins, it generally becomes more mineralized. Calcium-bicarbonate type water is dominant in and near recharge areas, whereas sodium levels generally increase relative to calcium and sulfate, and chloride dominates over bicarbonate, in deeper aquifers. In general, groundwater quality tends to be better in more productive bedrock aquifers because more active groundwater circulation provides less opportunity and time for minerals present in the rock to dissolve.

Sections 5.6.1.1 – 5.6.1.5 contain descriptions of the methods used to access, screen, and statistically summarize water quality data for this report. Detailed discussion of water quality analyses of samples collected from the Bear River Basin aquifers and their component geologic and lithostratigraphic units is provided in **Chapter 7**.

5.5.1 Groundwater quality

This section describes how data on chemical constituents for the Bear River Basin groundwater study were accessed, compiled, screened, and statistically summarized. A discussion of the physical and chemical characteristics of the hydrogeologic units defined for this study (**Pl. 5**) is provided in **Chapter 7**.

Groundwater quality in Wyoming is regulated by two agencies. The Wyoming Department of Environmental Quality (WDEQ) Water Quality Division (WQD) regulates groundwater quality in Wyoming, and the U.S. Environmental Protection Agency (USEPA) Region 8 Office, headquartered in Denver, regulates the public water

systems located within the State. Each agency has established groundwater standards, and revises and updates them periodically.

Groundwaters in Wyoming are classified with respect to water quality in order to apply these standards. The State of Wyoming through the WDEQ/WQD has classified the groundwaters of the State, per Water Quality Rules and Regulations, **Chapter 8** – Quality Standards for Wyoming Groundwaters (http://deq.state.wy.us/wqd/ WQDrules/Chapter_08.pdf), as:

- Class I Groundwater of the State – Groundwater that is suitable for domestic use.
- Class II Groundwater of the State – Groundwater that is suitable for agricultural (irrigation) use where soil conditions and other factors are adequate for such use.
- Class III Groundwater of the State – Groundwater that is suitable for livestock.
- Class Special (A) Groundwater of the State – Groundwater that is suitable for fish and aquatic life.
- Class IV Groundwater of the State – Groundwater that is suitable for industry.
- Class IV(A) Groundwater of the State – Groundwater that has a total dissolved solids (TDS) concentration not in excess of 10,000 milligrams per liter (mg/L). This level of groundwater quality in an aquifer is considered by the USEPA under Safe Drinking Water Act (SDWA) provisions as indicating a potential future drinking water source with water treatment.
- Class IV(B) Groundwater of the State – Groundwater that has a TDS concentration in excess of 10,000 mg/L.
- Class V Groundwater of the State – Groundwater that is closely associated with commercial deposits of hydrocarbons (oil and gas) (Class V, Hydrocarbon Commercial) or other minerals (Class V, Mineral Commercial), or is a geothermal energy resource (Class V, Geothermal).

5.5.1.1 Standards of groundwater quality

In this report, groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (**Table 5-1**) and summary statistics for environmental and produced water samples tabulated by hydrogeologic unit as quantile values (**Appendices E** and **F**, respectively). In assessing suitability for domestic use (Wyoming Class I groundwater), USEPA health-based standards of Maximum Contaminant Levels (MCLs) and Health Advisory Levels (HALs) are used as guides (however, these standards are not legally enforceable for any of the sampling sites used in this study). USEPA Secondary Maximum Contaminant Levels (SMCLs), which generally are aesthetic standards for domestic use, and WDEQ Class II groundwater standards for agriculture, Class III standards for livestock and Class IV standards for industry are used as guides for assessing suitability.

Many groundwater samples used in this study were not analyzed for every constituent for which a standard exists. In this report, the assessment of suitability of water for a given use is based only on the concentrations of constituents determined; the concentration of a constituent not determined could possibly make the water unsuitable for a given use.

Water-quality concentrations are compared to three types of USEPA standards: MCLs, SMCLs, and lifetime HALs. The USEPA MCLs (U.S. Environmental Protection Agency, 2012) are legally enforceable standards that apply to public water systems that provide water for human consumption through at least 15 service connections, or regularly serve at least 25 individuals. The purpose of MCLs is to protect public health by limiting the levels of contaminants in drinking water. MCLs do not apply to groundwater for livestock, irrigation, or self-supplied domestic use. They are, however, a valuable reference when assessing the suitability of water for these uses.

USEPA SMCLs (U.S. Environmental Protection Agency, 2012) are non-enforceable guidelines regulating contaminants in drinking water that may cause cosmetic effects (such as skin or tooth discoloration) or have negative aesthetic effects (such as taste, odor, or color) in drinking water. HALs are based on concentrations of chemicals in drinking water that are expected to cause any adverse or carcinogenic effect over a lifetime of exposure (U.S. Environmental Protection Agency, 2012). Because of health concerns, the USEPA has proposed two drinking-water standards for radon (U.S. Environmental Protection Agency, 1999)—an MCL of 300 picocuries per liter (pCi/L) and an alternative MCL (AMCL) of 4,000 pCi/L for communities with indoor air multimedia-mitigation programs. Radon concentrations herein are compared, and exceedance frequencies calculated, in relation to the formerly proposed MCL of 300 pCi/L.

Water-quality standards for Wyoming Class II, Class III, and Class IV groundwater (Wyoming Department of Environmental Quality, 1993) also are used for comparisons in this report. Class II groundwater is water that is suitable for agricultural (irrigation) use where soil conditions and other factors are adequate. Class III groundwater is water that is suitable for livestock watering. Class IV groundwater is water that is suitable for industry. The Class IV TDS standard (10,000 mg/L) also corresponds to the USEPA underground source of drinking water (USDW) TDS standard established as part of underground injection control (UIC) regulations. These Wyoming standards are designed to protect groundwater that meets the criteria of a given class from being degraded by human activity. They are not meant to prevent groundwater that does not meet the standards from being used for a particular use. Like the USEPA standards, they serve only as guides in this report to help assess the suitability of groundwater for various uses.

5.5.1.2 Sources, screening, and selection of data

Groundwater-quality data compiled through 2011 were gathered from the USGS National Water Information System (NWIS) database (http://

waterdata.usgs.gov/wy/nwis/qw/), the USGS Produced Waters Database (PWD) (http://energy. cr.usgs.gov/prov/prodwat/), the Wyoming Oil and Gas Conservation Commission (WOGCC) database, the University of Wyoming Water Resources Data System (WRDS) database, and other sources such as consultant reports prepared in relation to development of public water supplies. Methods used to screen data differ among the data sources, but the overall objective of all screening was to identify and remove samples that (1) were duplicates; (2) were not assigned to hydrogeologic units or were assigned to hydrogeologic units that contradicted local geologic information, particularly for shallow wells; (3) had inconsistent water-chemistry information such as poor ion balances or substantially different values of total dissolved solids and the sum of major ions; or (4) were unlikely to represent the water quality of a hydrogeologic unit because of known anthropogenic effects; for example, samples from wells monitoring known or potential point-source contamination sites or mining spoils sites. Groundwater-quality sample locations retained after data screening, and used herein, are shown on **Plate 3**.

Many of the groundwater sites in the Bear River Basin had been sampled more than once; however, only one groundwater sample from a given site was selected for this study, to avoid biasing the statistical results in favor of multiple-sample sites. An exception involved some sets of PWD samples from the same well at different depths and from different hydrogeologic units. In choosing among multiple samples from a site or well/hydrogeologic-unit combination, either the most recent sample, the sample with the best ion balance, or the sample with the most complete analysis was retained in the final dataset.

Chemical analyses of groundwater-quality samples available from the USGS PWD were included in the dataset used for this report. Produced water is water co-produced with oil and gas. The PWD includes samples within the Bear River Basin. Only those PWD samples from a wellhead or from a drill-stem test were included in the dataset. Samples that had not been assigned to

a hydrogeologic unit were removed from the dataset. The PWD samples were then screened to retain a single sample per well/hydrogeologic-unit combination. Some samples were removed because their water chemistry was identical to that of other samples, indicating probable duplication of sample records. PWD documentation indicated that samples generally had been screened to remove samples showing an ion balance greater than 15 percent—strictly, an imbalance between anion and cation activity of greater than 15 percent. The PWD generally contains chemical analyses for major ions and TDS. According to PWD documentation, some sample analyses may have reported the sum of sodium and potassium concentrations as sodium concentration alone.

Chemical analyses of groundwater-quality samples available from the WOGCC database (http://wogcc.state.wy.us/) were included in the dataset used for this report. Major-ion balances were calculated for these samples. Samples with an ion balance of greater than 10 percent generally were removed from the dataset, but some samples with an ion balance of between 10 and 15 percent from areas with few samples were retained.

Chemical analyses of groundwater-quality samples available from the WRDS database (http://www.wrds.uwyo.edu/) were included in the dataset used for this report when information was available to identify the hydrogeologic unit, locate the spring or well, and the site was not included in the USGS NWIS database. In addition, WDEQ monitoring wells located at sites of known or potential groundwater contamination were removed from the dataset because the objective of this study is to describe general groundwater quality based on natural conditions. Samples showing an ion balance greater than 10 percent were removed from the WRDS dataset.

Groundwater quality in the Bear River Basin varies widely, even within a single hydrogeologic unit. Water quality in any given hydrogeologic unit tends to be better near outcrop areas where recharge occurs, and tends to deteriorate as the distance from these outcrop areas increases (and residence time increases). Consequently, water

quality in a given hydrogeologic unit generally deteriorates with depth.

Many of the water-quality samples from aquifers in Quaternary- and Tertiary-age hydrogeologic units came from wells and springs that supplied water for livestock and wildlife. Wells that do not produce usable water generally are abandoned, and springs that do not produce usable water typically are not developed. In addition, where a hydrogeologic unit is deeply buried, it generally is not used for water supply if a shallower supply is available. For these reasons, the groundwater-quality samples from aquifers in the Quaternary-, Tertiary-, and some Cretaceous-age hydrogeologic units most likely are biased toward better water quality, and do not represent random samples. Although this possible bias likely does not allow for a complete characterization of the water quality of these hydrogeologic units, it probably allows for a more accurate characterization of the units in areas where they are shallow enough to be used economically.

Many of the groundwater-quality samples used in this study to characterize Mesozoic- and Paleozoic-age hydrogeologic units are produced-water samples from the USGS PWD and WOGCC databases. Although from oil and gas production areas, these samples probably have less bias in representing ambient groundwater quality than samples used to characterize Quaternary- and Tertiary-age hydrogeologic units.

5.5.1.3 Water quality characteristics

The TDS concentration in groundwater tends to be high with respect to the USEPA SMCL in most of the Bear River Basin, even in water from shallow wells. This is not surprising, given the arid climate and small rate of recharge in much of the study area. High TDS can adversely affect the taste and odor of drinking water, and a high TDS concentration in irrigation water has a negative effect on crop production. High TDS concentrations also cause scale build-up in pipes and boilers. The USEPA has not set an MCL for TDS; however, the USEPA SMCL for TDS is 500 milligrams per liter (mg/L) (U.S. Environmental Protection Agency, 2012). The TDS concentration

is loosely termed salinity. Groundwater samples are classified in this report in accordance with the USGS salinity classification (Heath, 1983), as follows:

Classification	TDS
Fresh	0–999 mg/L
Slightly saline	1,000–2,999 mg/L
Moderately saline	3,000–9,999 mg/L
Very saline	10,000–34,999 mg/L
Briny	more than 34,999 mg/L

The sodium-adsorption ratio (SAR) represents the ratio of sodium ion activity (concentration) to calcium and magnesium ion activities; it is used to predict the degree to which irrigation water enters into cation-exchange reactions in the soil. High SAR values indicate that sodium is replacing adsorbed calcium and magnesium in soil, which damages soil structure and reduces permeability of the soil to water infiltration (Hem, 1985). The SAR is used in conjunction with information about the soil characteristics and irrigation practices in the area being examined. The high SAR of waters in some hydrogeologic units in the Bear River Basin indicates that these waters may not be suitable for irrigation.

Many groundwater-quality samples included in the dataset for this report contain high concentrations of sulfate, chloride, fluoride, iron, and manganese, with respect to USEPA standards (U.S. Environmental Protection Agency, 2012) and WDEQ groundwater-quality standards (http://deq. state.wy.us/wqd/WQDrules/Chapter_08.pdf). As expected, concentrations in samples of produced water (defined in a following section, "Produced-water samples") commonly exceeded many USEPA and WDEQ standards.

Sulfate in drinking water can adversely affect the taste and odor of the water, and may cause diarrhea (U.S. Environmental Protection Agency, 2012). The USEPA SMCL for sulfate is 250 mg/L, and the WDEQ Class III groundwater (livestock) standard is 3,000 mg/L. High chloride concentrations can adversely affect the taste of drinking water, increase the corrosiveness of water, and damage salt-sensitive crops (U.S.

Environmental Protection Agency, 2012; Bohn et al., 1985, and references therein). The USEPA SMCL for chloride is 250 mg/L, the WDEQ Class II groundwater (agricultural) standard is 100 mg/L, and the WDEQ Class III groundwater (livestock) standard is 2,000 mg/L.

High fluoride concentrations commonly are associated with produced water from deep hydrogeologic units in sedimentary structural basins. Low concentrations of fluoride in the diet have been shown to promote dental health, but higher doses can cause health problems such as dental fluorosis—a discoloring and pitting of the teeth—and bone disease (U.S. Environmental Protection Agency, 2012). The USEPA SMCL for fluoride is 2.0 mg/L, and the MCL is 4.0 mg/L.

Both iron and manganese may adversely affect the taste and odor of drinking water and cause staining (U.S. Environmental Protection Agency, 2012). The USEPA has established SMCLs of 300 micrograms per liter (μg/L) for iron and 50 μg/L for manganese. High concentrations of iron and manganese in irrigation water may have a detrimental effect on crop production (Bohn and others, 1985, and references therein).

5.5.1.4 Statistical analysis

In relation to groundwater quality, analysis has two meanings in this report, *chemical analysis* and *statistical analysis*. Chemical analysis of a water sample is the determination (or the description) of the concentration of chemical species dissolved in the water; for example, *the concentration of calcium in the sample is 6 mg/L* (6 milligrams of calcium per liter of water). The chemical analysis may include physical measurements of chemical properties such as pH (a measure of hydrogen ion activity). The statistical analysis of a set of chemical analyses is the mathematical treatment of the dataset to describe and summarize those data in order to convey certain useful descriptive characteristics; for example, *the calcium concentration in groundwater samples from this hydrogeologic unit ranges from 5.0 to 20 mg/L per liter, with a median concentration of 17 mg/L per liter.*

Table 5-1. Selected groundwater quality standards and advisories.

Physical characteristics and constituents		Groundwater quality and standards				
		Domestic[1]			Agricultural[2] Class II	Livestock[2] Class III
		MCL	SMCL USEPA	HAL	WDEQ-WQD	
	pH (standard units)		6.50-8.50		4.5-9.0	6.5-8.5
Major ions and related properties (mg/L)	chloride (Cl-)		250		100	2,000
	fluoride (F-)	4	2			
	sulfate (SO42-)		250		200	3,000
	TDS		500		2,000	5,000
	SAR (ratio)				8	
Trace elements (µg/L)	aluminum (Al)		50-200		5,000	5,000
	antimony (Sb)	1				
	arsenic (As)	10			100	200
	barium (B)	2,000				
	beryllium (Be)	4			100	
	boron (B)			1,000	750	5,000
	cadmium (Cd)	5			10	50
	chromium (Cr)	100			100	50
	cobalt (Co)				50	1,000
	copper (Cu)	1,300	1,000		200	500
	cyanide3 (CN-)	200				
	iron (Fe)		300		5,000	
	lead (Pb)	15			5,000	100
	lithium (Li)				2,500	
	manganese (Mn)		50		200	
	mercury (Hg)	2				0.10
	molybdenum (Mo)			40		
	nickel (Ni)			100	200	
	selenium (Se)	50			20	50
	silver (Ag)		100			
	thallium (Ti)	2		0.5		
	vanadium (V)				100	100
	zinc (Zn)		5,000	2,000	2,000	25,000
Nutrients (mg/L)	nitrate (NO3-), as N	10				
	nitrite (NO2-), as N	1				10
	nitrate + nitrite, as N					100
	ammonium (NH4+)			30		
Radiochemicals (rCi/L)	gross-alpha radioactivity4	15			15	15
	strontium-90 (strontium)			4	8	8
	radium-226 plus radium-228	5			5	5
	radon-222 (radon)5	300/4,0005				
	uranium (μg/L)	30				

Table 5-1. cont.

[1] USEPA 2012
[2] WDEQ, 2005
[3] Trace ion, included for convenience
[4] Includes radium-226 but excludes radon-222 and uranium

MCL, Maximum Contaminant Level SMCL, Secondary Maximum Contaminant Level HAL, Lifetime Health Advisory Level USEPA, U. S. Environmental Protection Agency WDEQ-WQD, WDEQ Water Quality Division	N, nitrogen mg/L, milligrams per liter (ppm) μg/L micrograms per liter (ppb) pCi/L, picocuries per liter SAR, sodium adsorption ratio TDS, total dissolved solids

The statistical analysis of a set of chemical analyses is the mathematical treatment of the dataset to describe and summarize those data in order to convey certain useful descriptive characteristics; for example, *the calcium concentration in groundwater samples from this hydrogeologic unit ranges from 5.0 to 20 mg/L per liter, with a median concentration of 17 mg/L per liter.*

This section describes the approaches used to assemble, analyze, and present water-quality data for samples of groundwater from the Bear River Basin. Supplementary data Tables contain all the data used in this chapter - data too numerous for inclusion in the report, but available online at http://waterplan.state.wy.us/plan/bear/bear-plan.html. From these data, *summary statistics* were derived for physical properties and major-ion chemistry of groundwater in hydrogeologic units in the Bear River Basin, as tabulated in **Appendix E** for environmental water samples, and **Appendix F** for produced-water samples. *Environmental water* is natural groundwater as produced from wellheads and springs; it is not associated with hydrocarbons. *Produced water* is water co-produced (pumped out of the ground) with oil and gas. The water-quality data for the hydrogeologic units in the Bear River Basin also are compared to USEPA and WDEQ standards for various water uses, as the *groundwater-quality standard exceedance frequencies* presented in this report.

Standard summary statistics (Helsel and Hirsch, 1992) for uncensored data were used for physical characteristics and major-ion chemistry

(**Appendices E and F**). Standard summary statistics also were included for iron concentrations from produced waters. Censored data are data reported as above or below some threshold, such as "below detection limit" or "less than 1 mg/L." For a very small number of major-ion samples, censored values ("less-than") were reported for a major-ion constituent. These censored values were treated as uncensored values at the laboratory reporting level, for statistical analysis. For uncensored datasets with a sample size of 1, only a minimum value is reported in **Appendices E and F**; for a sample size of 2, minimum and maximum values are reported; for a sample size of 3, minimum, median (50th percentile), and maximum values are reported; for sample sizes of 4 or more, minimum, 25th percentile, median (50th percentile), 75th percentile, and maximum values are reported.

Concentrations of nutrient, trace element, and radiochemical constituents were reported as uncensored values in environmental water datasets for some hydrogeologic units. For nutrient, trace element, and radiochemical datasets without censored values, the convention used for uncensored data was used to report summary statistics. Environmental water datasets for other hydrogeologic units contained censored values, including censored values that had multiple detection limits. Rather than assign the laboratory reporting level or another arbitrary value to the censored results, the Adjusted Maximum Likelihood Estimation (AMLE) technique was used for statistical analysis of nutrients, trace elements, and radiochemical constituents in this report.

interquartile range and determines the maximum uncensored value for the dataset; therefore, the summary statistics presented in the report for nutrients, trace elements, and radiochemical constituents are the 25th percentile, median, 75th percentile, and maximum. In some cases, environmental water datasets for a constituent and hydrogeologic unit could not meet the minimum sample size or uncensored value requirements for the AMLE technique. In those cases, constituents within a hydrogeologic unit that had a sample size of 1, a minimum value (censored or uncensored) is reported, and for a sample size of 2, a minimum value (censored or uncensored) and maximum value are reported, or only a maximum censored value is reported. In those cases where the sample size was sufficient, but the AMLE technique failed to compute percentiles, only a maximum value (censored or uncensored) is reported. For a few constituents that did not have any censoring, standard summary statistics could be determined and are reported. In some cases, a dataset for a constituent and hydrogeologic unit was insufficient for determining complete summary statistics with the AMLE technique; however, individual samples could be used for groundwater-quality exceedance analysis.

Groundwater-quality standard exceedance frequencies are described for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards. Groundwater-quality standard exceedance frequencies were calculated and reported as a percentage for a hydrogeologic unit. When only one sample was available and exceeded a standard, the text indicates one sample exceeded a standard, rather than indicating '100 percent.' Groundwater-quality standard exceedance frequencies were determined using the filtered analyses for a constituent because filtered analyses were more common (or frequently were the only analyses available). Only samples for a constituent that were analyzed at a laboratory reporting level that was equal to or less than the specific groundwater-quality standard for that constituent were included in the exceedance analysis. For example, if five samples were analyzed for manganese and the results were <10 μg/L, <20 μg/L, 53 μg/L, 67 μg/L, and <100 μg/L, only the

four samples with results of <10 μg/L, <20 μg/L, 53 μg/L, and 67 μg/L could be compared to the SMCL of 50 μg/L for manganese. The sample with the value of <100 μg/L could not be used because it cannot be determined if its value was less than 50 μg/L or greater than 50 μg/L. For this example, the groundwater quality exceedance text would indicate that 50 percent of samples exceeded the SMCL of 50 μg/L. Complete summary statistics for manganese would not be included in the appendix for the hydrogeologic unit in this example because too many of the available values were censored for the AMLE technique to calculate summary statistics. The AMLE technique criterion of having three uncensored values in the dataset was not met. For this example, only a maximum value of <100 μg/L would be reported in the appendix. Descriptions of the constituents that were included in the statistical summaries for environmental water samples and produced-water samples are summarized in the next section.

5.5.1.4.1 Environmental water samples

Environmental water samples ("environmental waters") are from wells of all types except those used for resource extraction (primarily oil and gas production) or those used to monitor areas with known groundwater contamination. The environmental water samples used in this report were compiled from the USGS NWIS database, the WRDS database, and other sources such as consulting engineers' reports related to water supply exploration and development. The physical properties and constituents presented in this report are pH, specific conductance, major ions, nutrients, trace elements, and radiochemicals.

Physical properties of environmental waters, which generally are measured in the field on unfiltered waters, were pH (reported in standard units), specific conductance (reported in microsiemens per centimeter at 25 degrees Celsius), and dissolved oxygen. If field values were not available, laboratory values were used.

Major-ion chemistry of environmental waters, comprising major ions and associated properties or constituents, was reported as laboratory analyses

of filtered waters (or constituents were calculated from laboratory analyses). Major-ion chemistry constituents and related properties were hardness (calculated and reported as calcium carbonate), dissolved calcium, dissolved magnesium, dissolved potassium, sodium-adsorption ratio (calculated), dissolved sodium, alkalinity (reported as calcium carbonate), dissolved chloride, dissolved fluoride, dissolved silica, dissolved sulfate, and total dissolved solids.

For this report, a measured laboratory value of TDS (residue on evaporation at 180 degrees Celsius) commonly was available and included in the dataset. If a laboratory value was not available, a TDS value was calculated by summing concentrations of individual constituents (if complete analyses were available). For this report, a filtered laboratory value of alkalinity was included in the dataset if available. If that was not available, an unfiltered laboratory value of acid-neutralizing capacity (ANC) was used for alkalinity; if that constituent was not available, a filtered field alkalinity value was used; and if that was not available, an unfiltered field value of ANC was used to report alkalinity. These constituents are reported in milligrams per liter (µg/L).

Because there were many different types of laboratory analyses, including different analytical methods and different reporting forms (for example, concentrations reported as nitrate or as nitrogen), only a subset of the nutrient constituents were selected from the final datasets and used for calculation of summary statistics. Nutrient constituents in environmental waters, analyzed in a laboratory using filtered water samples, that were included in the summary statistics are dissolved ammonia (reported as nitrogen), dissolved nitrate plus nitrite (reported as nitrogen), dissolved nitrate (reported as nitrogen), dissolved nitrite (reported as nitrogen), dissolved orthophosphate (reported as phosphorus), and dissolved phosphorus (reported as phosphorus). In addition, total phosphorus (reported as phosphorus), analyzed in a laboratory using unfiltered water samples, also was included in the summary statistics. These constituents are reported in milligrams per liter. All nutrient constituents, regardless of method or reporting

form, were included in the final datasets that were used for calculation of groundwater-quality standard exceedance frequencies; therefore, a value that was used to construct the exceedance frequency tables may not be listed in the summary statistics tables.

Trace element constituents in environmental waters, analyzed in a laboratory using filtered water samples, that were included in the datasets for this report were dissolved aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, chromium, cobalt, copper, iron, lead, lithium, manganese, mercury, nickel, selenium, silver, thallium, vanadium, and zinc. In addition, total iron (unfiltered) and total manganese (unfiltered) were included in the datasets. These constituents are reported in micrograms per liter (µg/L).

Radiochemical constituents in environmental waters, analyzed in a laboratory using filtered water samples, that were included in the datasets for this report were dissolved alpha radioactivity (using thorium-230 curve method), gross beta radioactivity, dissolved radium-226, dissolved radium-226 (using a radon method), dissolved radium-228, dissolved uranium (natural), radon-222 (unfiltered) (referred to herein as "radon"). All radiochemical constituents are reported as picocuries per liter (pCi/L) except uranium, which is reported as micrograms per liter (µg/L).

5.5.1.4.2 Produced-water samples

Produced-water samples are from wells related to natural resource extraction (primarily oil and gas production). Chemical analyses for produced-water samples were compiled from the WOGCC database and the USGS PWD. The physical properties and constituents presented in this report for produced-water samples are pH, major ions, and trace elements. Nutrients were not included because nitrate was the only constituent available; nitrate was infrequently reported in the sample analyses, and the form (whether as nitrate or as nitrogen) was not reported. Radiochemical data were used to calculate exceedance frequencies, but were not used to calculate summary statistics

because radium-226 was the only constituent available; radium-226 was infrequently reported with the sample analyses, and the reporting units were unknown.

The physical properties, major ion chemistry, and trace elements summarized for produced waters in this report generally were the same as for environmental waters, with some exceptions. In the produced-waters dataset, the water phase (filtered or unfiltered) was not reported with the data so the analyses may include a mix of dissolved and total concentrations. The physical properties and major-ion chemistry characteristics statistically analyzed herein are pH (in standard units), calcium, magnesium, potassium, sodium-adsorption ratio (calculated), sodium, bicarbonate (reported as bicarbonate), carbonate (reported as carbonate), chloride, fluoride, silica, sulfate, and total dissolved solids (TDS). The method for determining TDS concentrations was not reported with the data. The reporting unit for major-ion chemistry was milligrams per liter. Iron was the only trace element summarized; iron concentrations in the original database were reported in milligrams per liter and were converted to micrograms per liter for the statistical summary.

5.5.1.5 Trilinear diagrams

The relative ionic composition of groundwater samples from springs and wells in the Bear River Basin study area are plotted on trilinear diagrams (Appendices G and H). A trilinear diagram, also frequently referred to as a Piper diagram (Piper, 1944), provides a convenient method to classify and compare water types based on the ionic composition of different groundwater samples (Hem, 1985). Cation and anion concentrations for each groundwater sample are converted to total milliequivalents per liter (a milliequivalent is a measurement of the molar concentration of the ion, normalized by the ionic charge of the ion) and plotted as percentages of the respective totals into triangles (Appendices G and H). The cation and anion relative percentages in each triangle are then projected into a quadrilateral polygon that describes a water type or hydrochemical facies (see Back, 1966).

5.6 Aquifer sensitivity and potential groundwater contaminant sources

This report provides an evaluation of the types of contamination that potentially threaten groundwater resources in the Bear River Basin. It is axiomatic that protecting groundwater from contamination is much more attainable than remediation should the resource be impacted by unsound practices.

In 1992 the Wyoming Department of Environmental Quality/Water Quality Division (DEQ/WQD), in cooperation with the University of Wyoming, the Wyoming Water Resources Center (WWRC), the Wyoming State Geological Survey (WSGS), the Wyoming Department of Agriculture (WDA), and the U.S. Environmental Protection Agency (EPA), Region VIII, initiated the Wyoming Ground Water Vulnerability Mapping Project to evaluate the vulnerability of the state's groundwater resources to contamination. This effort resulted in the publication of the Wyoming Groundwater Vulnerability Assessment Handbook (the Handbook) by the Spatial Data and Visualization Center (SDVC; Hamerlinck and Arneson, 1998). While the fundamental goal of the SDVC study was to develop a GIS-based tool to aid in planning, decision-making, and public education, the GIS maps and associated digital databases developed by the project have been used for numerous subsequent, related studies such as updates to the State Water Plan. The SDVC aquifer sensitivity map and the associated GIS precipitation and recharge data are used in this study to evaluate aquifer-specific recharge (**Chapter 6**). The methodology and purpose of the 1998 SDVC report are discussed in this section.

Two maps from the 1992 SDVC study are used to evaluate the potential for groundwater contamination in the Bear River Basin: 1) a map of average annual recharge (**Fig. 5-2**), and 2) a map of aquifer sensitivity (**Fig. 5-3**). **Figures 5-4** through **5-10** map potential groundwater contaminant sources in the Bear River Basin. Additional discussion on the rationale for and methodology used in developing **Figures 5-1** through **5-10** is provided in **Appendix C**.

5.6.1 The Wyoming Groundwater Vulnerability Assessment Handbook and aquifer sensitivity

The Wyoming Ground Water Vulnerability Mapping Project was initiated to develop GIS-based mapping approaches to: 1) assess the relative sensitivity and vulnerability of the state's groundwater resources to potential sources of contamination, primarily pesticides; 2) assist state and local agencies in identifying and prioritizing areas for groundwater monitoring; and 3) help identify appropriate groundwater protection measures. The *Handbook* distinguishes "groundwater vulnerability" and "aquifer sensitivity" as follows:

- *Aquifer sensitivity* refers to the relative potential for a contaminant to migrate to the shallowest groundwater, based solely on hydrogeologic characteristics. According to the SDVC, "Aquifer sensitivity is a function of the intrinsic characteristics of the geologic material between ground surface and the saturated zone of an aquifer and the aquifer matrix. Aquifer sensitivity is not dependent on land use and contaminant characteristics."

- *Groundwater vulnerability* considers aquifer sensitivity, land use, and contaminant characteristics to determine the vulnerability of groundwater to a specific contaminant. Because pollutant characteristics vary widely, the SDVC vulnerability assessments assumed a generic pollutant with the same mobility as water.

Aquifer sensitivity and groundwater vulnerability are characteristics that cannot be directly measured but must be estimated from measurable hydrogeologic and contaminant properties and land-use conditions. Because of the uncertainty inherent in the assessment of sensitivity and vulnerability, these parameters are not expressed quantitatively; but rather, in terms of relative potential for groundwater contamination. Because the SDVC vulnerability mapping assumed a single, generic pollutant, only the map of relative aquifer sensitivity is presented in this study. The aquifer sensitivity map (**Fig. 5-3**) may be compared with **Figures 5-4** through **5-10** to identify areas of elevated risk of contamination from specific potential groundwater contaminant sources.

The SDVC study assessed aquifer sensitivity using modified DRASTIC model methodology (Aller and others, 1985) based on six independent parameters:

- Depth to initial groundwater
- Geohydrologic setting
- Soil media
- Aquifer recharge (average annual)
- Topography (slope)
- Impact of the vadose zone

The SDVC rates each parameter on a scale from one to 10 based on how strongly it affects aquifer sensitivity; a higher value indicates a greater effect. Parameter ratings are then summed to obtain an index of sensitivity that ranges from six (lowest risk) to 60 (highest hazard).

There are substantial limitations associated with the SDVC sensitivity analysis and maps. The sensitivity map portrays only a relative assessment of susceptibility to groundwater contamination. The Wyoming sensitivity assessments cannot be compared to similar studies in adjacent states or other areas. The sensitivity assessments are not appropriate for stand-alone, site-specific application, and should be supplemented with additional investigations.

Figure 5-3 delineates five sensitivity categories for the Bear River Basin that reflect the relative potential for contaminants to migrate from the ground surface to the uppermost groundwater (water table).

- The highest risk areas (43-56) are located primarily over alluvial deposits; adjacent to rivers, streams, and lakes; and in the highly fractured mountain belts that surround the basins. The shallow depths to groundwater, high porosities

of unconsolidated soils and weathered bedrock, and relatively flat topography place alluvial aquifers at higher risk of contamination. Similarly, heavily fractured bedrock, shallow groundwater within thin soil zones, and high rates of recharge characteristic of mountainous aquifers make fractured mountain units highly vulnerable to contamination.

- Medium-high ranked areas (37-42) generally extend from the edges of the highest ranked areas, across adjacent alluvial or foothill zones. Groundwater in these areas generally occurs in deeper, thinner aquifers. The soils in these zones are more mature and have higher clay and loam contents. There is less fracturing in the bedrock exposed in the foothills than in more highly deformed, mountainous areas.

- Medium ranked areas (31-36) are prevalent in the remaining dry land agricultural and grazing areas of the Bear River Basin. These areas generally have relatively thicker, well-drained, mature soils; rolling topography with minor relief (lower slopes); and greater depths to the water table.

- Medium-low ranked areas (26-30) are generally characterized by low natural precipitation, low recharge, deep water Tables, rolling topography, and unfractured bedrock.

- Low ranked areas (18-25) have the deepest water Tables and lower hydraulic conductivity in the vadose zone. Soils in these areas are generally poor for agriculture due to high clay content, or due to very low average precipitation, or both.

5.6.2 Potential sources of groundwater contamination

Figures 5-4 through **5-10** illustrate potential groundwater contaminant sources in the Bear River

Basin. These generally include industrial, retail, private, and public facilities that manufacture, process, use, store, sell, dispose, or otherwise handle substantial volumes of waste and other substances with physical and chemical characteristics that, released to the environment, could migrate to the water table. Releases from these facilities would pose a potential threat primarily to unconfined aquifers and the outcrop/recharge areas of confined aquifers. **Figure 5-3** shows areas where migration to the water table is most likely.

Many human activities have the potential to contaminate underlying groundwater resources. Possible sources of contamination include the following broad economic sectors: farming and ranching; resource development such as oil and gas, mineral extraction and logging; construction; transportation; residential, industrial and commercial development, and recreational activities. This section examines the potential for contamination from various point sources, that is, sources of pollution that can be traced to single definable places.

The identification and mapping of facilities as potential sources of groundwater contamination *does not* imply that they are impacting groundwater resources Generally, these facilities are strictly regulated by one or more regulatory agency to prevent contaminant releases and to protect groundwater resources, human health, and the environment.

The following regulatory agencies, and the types of facilities that they regulate, provided the geospatial data used to generate **Figures 5-4** through **5-10**:

WDEQ Water Quality Division:
- Known contaminated sites regulated under the Groundwater Pollution Control Program
- Class I and V injection wells regulated under the Underground Injection Control (UIC) Program
- Wyoming Pollutant Discharge Elimination System (WYPDES), formerly National Pollutant Discharge Elimination System (NPDES), discharge points
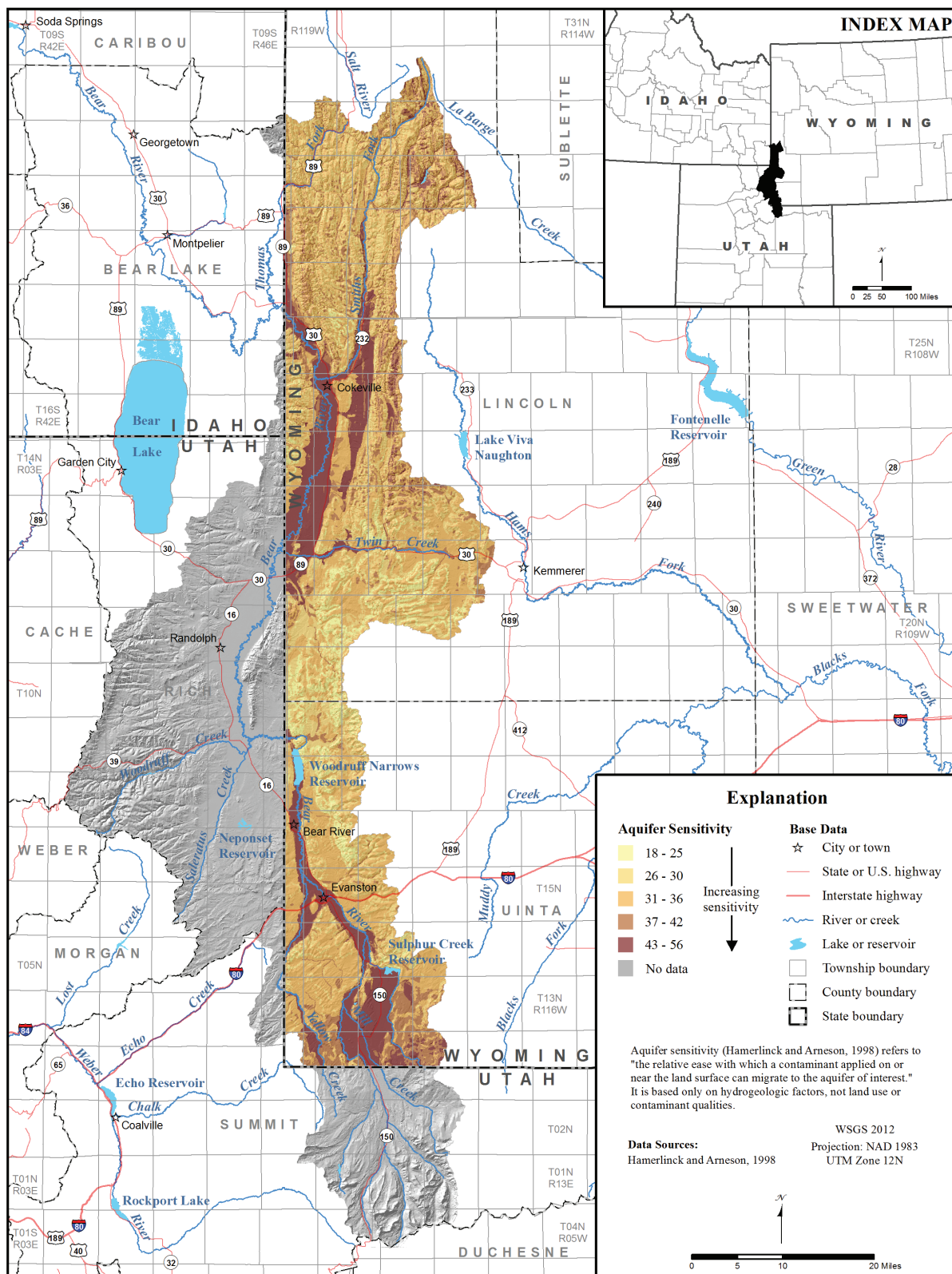
Figure 5-3. Aquifer sensitivity, Bear River Basin, Wyoming.

- Public owned treatment works (POTWs) and septic systems (Water and Wastewater Program)
- Confined animal feeding operations (CAFOs)
- Pesticides/herbicides (Nonpoint Source Program)
- Underground coal gasification sites

WDEQ Solid and Hazardous Waste Division:
- Known contaminated sites regulated under the Voluntary Remediation Program (VRP), including orphan and brownfield assistance sites
- Permitted disposal pits and other small treatment, storage, and disposal (TSD) facilities
- Landfills
- Above-ground and underground storage tanks

WDEQ Land Quality and Abandoned Mine Land Divisions:
- Class III injection wells used for mineral extraction
- Active, inactive, and abandoned mines, gravel pits, quarries, etc.

Wyoming Oil & Gas Conservation Commission:
- Active and abandoned Class II disposal and injector wells
- Produced water pits

Wyoming State Geological Survey:
- Oil and gas fields, plants, compressor stations
- Pipelines
- Mines (active and inactive)
- Gravel pits, quarries, etc.

These agencies were contacted to obtain available data suitable for mapping the various potential contaminant sources. Location data for similar potential contaminant sources were grouped for presentation on an abridged version of the surface hydrogeology map (**Pl. 2**): the groupings in **Figures 5-4** through **5-10** are generally not by agency, but rather by similarity of facilities and presentation considerations, primarily data point

density. Some areas of high data density have been scaled up as inserts on the potential contaminant sources maps.

Figure 5-4 – Potential groundwater contaminant sources: Oil and gas fields, pipelines, refineries, and WOGCC Class II injection and disposal wells

- **Oil and gas fields:** Oil and gas exploration, production, processing, and transportation facilities handle large volumes of petroleum hydrocarbons, produced water, and substantial volumes of other products that can pose a threat to groundwater such as fuel, methanol, glycols, amines, lubrication and hydraulic oils, acids, and a variety of well hydraulic fracturing and treatment chemicals. Large volumes of waste and wastewater are typically generated by oil and gas operations. Releases can occur from storage tanks, process vessels, and above-ground and underground piping. In some cases hydrocarbons, produced water, and other chemicals are discharged to pits constructed for a wide variety of applications. Older and abandoned pits were commonly unlined and; therefore, have greater potential for groundwater contamination. Prevention and mitigation of groundwater contamination resulting from releases of petroleum hydrocarbons is a primary area of concern and regulation by local, state, and federal agencies.

- **Pipelines:** Inter- and intrastate pipelines transport a variety of liquids that if released by rupture, malfunction, operational problems, or leaks can migrate to groundwater. Small leaks from buried pipelines can go undetected for extended periods of time, releasing substantial volumes of contaminants.

- **Active and permanently abandoned injector and disposal wells:** Wells for disposal or for maintaining reservoir pressure in enhanced oil recovery, among
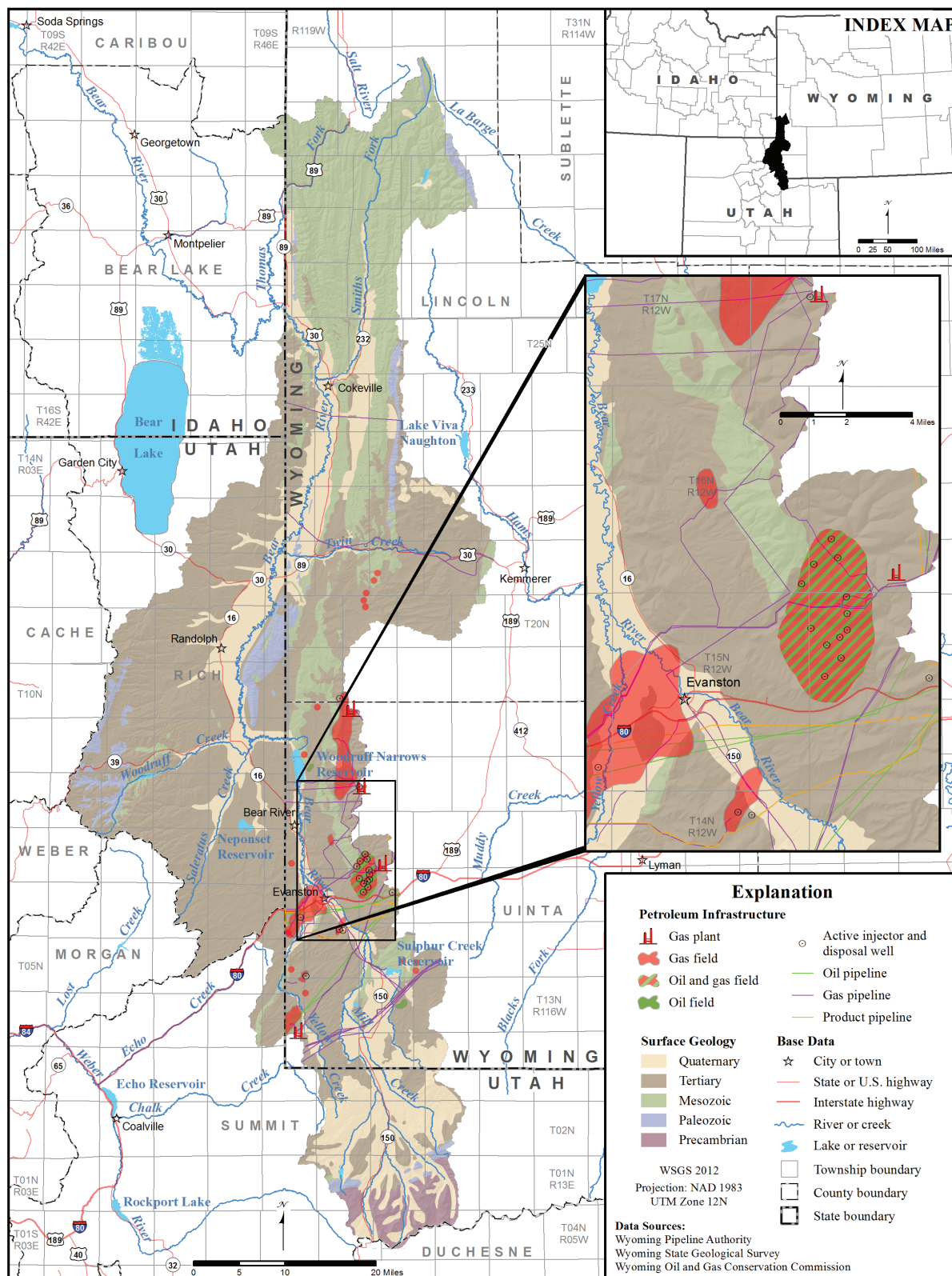
Figure 5-4. Potential groundwater contaminant sources: oil and gas fields, pipelines, gas processing plants, and Class II injection and disposal wells, Bear River Basin, Wyoming.

other purposes, are permitted by the WOGCC for injecting produced water into permeable zones that are deeper than and hydraulically isolated from useable groundwater resources. Injector wells are mapped as potential contaminant sources because there are several in the Bear River Basin and because they typically inject large volumes of produced water that could pollute groundwater resources if leaked into shallower aquifers. Injection facilities also employ bulk storage tanks, piping systems, and other equipment that can release produced water or other contaminants in recharge areas. Class II wells, strictly regulated by the WOGCC and the BLM/EPA, generally pose minimal potential for impacting groundwater resources by excursions from the injection interval; however, releases during surface operations or through poorly cemented well casing, though rare, are potential avenues of contamination. Class II injection wells are located within oil and gas fields.

Figure 5-5 – Potential groundwater contaminant sources: Class I and V injection wells in the WDEQ UIC Program

- **Class I and V UIC injection wells:** Class I underground injection wells and Class V injection facilities are regulated through the WDEQ Underground Injection Control (UIC) Program. In Wyoming, Class I wells inject non-hazardous wastes (Resource Conservation and Recovery Act RCRA definition) into hydraulically isolated, permeable zones that are deeper than, and isolated from, useable groundwater resources. Produced water disposal contributes a large component of injected fluids. Class I wells generally have minimal potential for impacting groundwater resources. Class I wells are mapped because of the wider range of liquid wastes they accept for injection. In contrast, Class V facilities inject a wide range of non-hazardous fluids generally

above or directly into shallow aquifers, and therefore have a substantial capacity for impacting groundwater resources. Many Class V wells in Wyoming are associated with groundwater contamination, and new injection of industrial wastes has been banned. Currently, only three Class V facilities permitted to inject industrial wastes are operational in the state of Wyoming and these must follow stringent annual monitoring requirements. Some notable examples of Class V facilities are agricultural or storm water drainage wells, large-capacity septic systems, automotive and industrial waste disposal wells, and various types of infiltration galleries. Class I and Class V injection facilities also generally include bulk storage tanks, pipelines, and other equipment that could release contaminants in recharge areas.

- **Class III injection wells:** Class III injection wells are permitted through the WDEQ Land Quality Division (LQD). Class III wells inject fluids for in situ solution mining of various minerals (e.g., uranium, sulfur, copper, trona, potash), for underground coal gasification, for the recovery of hydrocarbon gas and liquids from oil shale and tar sands, and for experimental/pilot scale technology.

Figure 5-6 – Potential groundwater contaminant sources: WQD groundwater pollution control facilities, commercial oil pits, and active and expired outfalls in the Wyoming Pollutant Discharge Elimination System (WYPDES) program

- **Known contaminated areas:** These sites are generally regulated by the WQD Groundwater Pollution Control Program. They include sites with confirmed soil and groundwater contamination that have not entered the VRP and are being addressed under orders from the WDEQ.
- **Commercial wastewater disposal pits:** Commercial wastewater disposal pits are regulated by the WDEQ Water
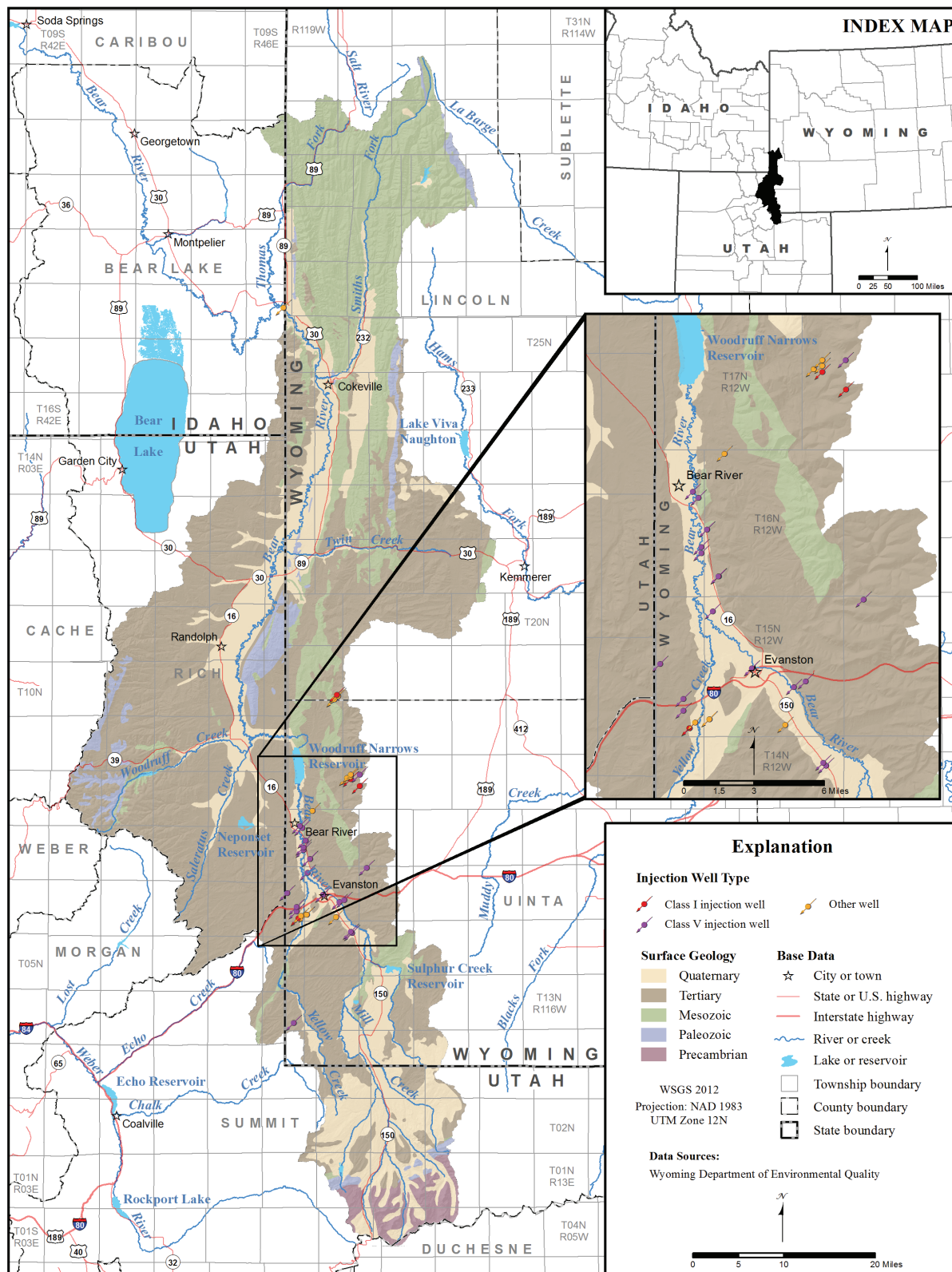
Figure 5-5. Potential groundwater contaminant sources: Class I and V injection wells permitted through the Wyoming Department of Environmental Quality Underground Injection Control (UIC) program, Bear River Basin, Wyoming.
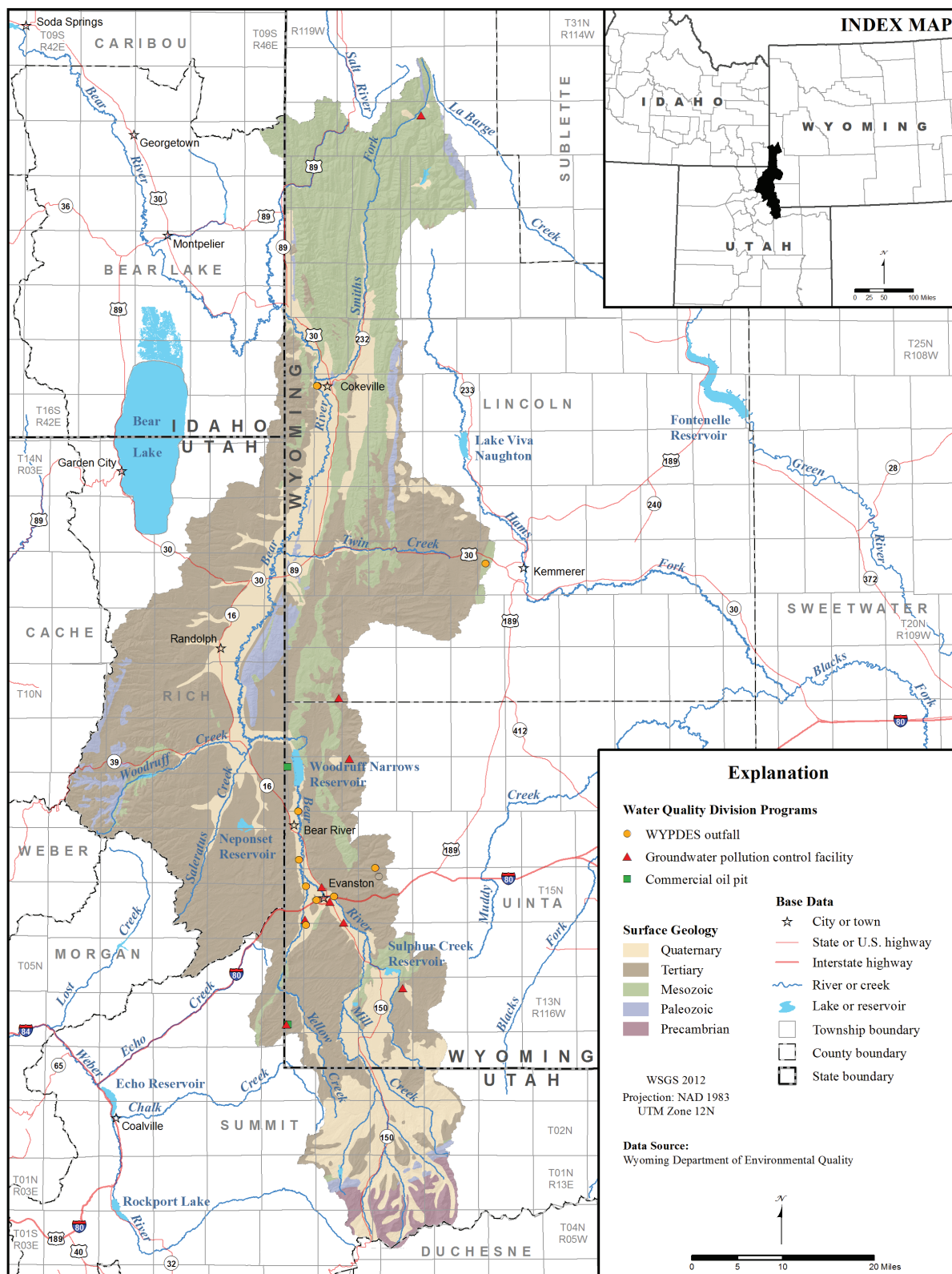
Figure 5-6. Potential groundwater contaminant sources: Active and expired outfalls in the Wyoming Pollutant Discharge Elimination System (WYPDES) program; WDEQ groundwater pollution control facilities and commercial disposal pits, Bear River Basin, Wyoming.

Quality Division (WQD) Water and Wastewater Program. These facilities deal primarily with produced water from oil and gas operations but can receive other wastes with prior approval of the WDEQ. Produced water disposed at these facilities is commonly accompanied by liquid hydrocarbons, which are generally recovered and sold prior to wastewater injection. Releases can occur from operational malfunctions, leaking from surface pits, and leaks from pipes and storage tanks.

- **Active and expired WYPDES outfalls:** Discharge of any potential pollutant from a point source into surface waters of the state requires a Wyoming Pollutant Discharge Elimination System (WYPDES) permit. During flow to surface waters where contaminant concentrations may be diluted, discharged waters may infiltrate dry drainages and recharge shallow aquifers, potentially contaminating groundwater resources. Spreader dikes, on-channel reservoirs, ponds, pits, and other impoundments are commonly installed along WYPDES flow paths to store water for other uses, and to slow flow rates to minimize erosion and remove sediment. These installations all enhance the amount of surface flow that can infiltrate into the subsurface by increasing the time and area over which discharged water is in contact with the stream channel or storage basin. WYPDES outfalls are associated with a variety of facilities in the Bear River Basin, several of which discharge produced water from oil and gas operations.

Figures 5-7 through **5-9** show the locations of active and abandoned mines, quarries, pits, and similar operations. These facilities and sites can impact groundwater in several ways. Stripping topsoil from an area increases infiltration rates and removes the capacity for biodegradation and retardation of contaminants within the soil horizon. Excavations can impound large quantities of water and enhance recharge or can

hydraulically connect contaminants to the water table. Atmospheric exposure of metal-rich minerals can oxidize and mobilize through dissolution. In addition, any release of bulk products (fuel, antifreeze, lubrication and hydraulic oils, etc.) more quickly infiltrates the subsurface within disturbed areas associated with the operations of these facilities.

Figure 5-7 – Potential groundwater contaminant sources: WDEQ/Abandoned Mine Land (AML) Program, abandoned mine sites - shows the location of abandoned mine sites inventoried and under the jurisdiction of the WDEQ AML Division. These include sites where reclamation may or may not have been completed.

Figure 5-8 – Potential groundwater contaminant sources: WDEQ Land Quality Division (LQD) permitted mines, quarries and pits

Three active mine types are regulated by the WDEQ Land Quality Division (LQD):

- **Active limited mining operations (LMO)** are exempt from the WDEQ's full permitting process. LMOs are restricted to a maximum of 10 acres for the life of the mine.
- **Active small mines** may disturb up to 10 acres per year but do not have a limit on the total area disturbed.
- **Active large mines** have no limit on total disturbance area or on how many acres may be disturbed per year.
- **Active coal mines** mapped by the WSGS are also included in **Figure 5-8**.

Figure 5-9 – Potential groundwater contaminant sources: WSGS mapped mines, pits, mills, and plants - includes active, inactive, abandoned, and proposed facilities and sites, partially duplicating mine sites shown on **Figures 5-8** and **5-9**. However, because the data for **Figure 5-9** was compiled prior to and independently of the data compiled for **Figures 5-7** and **5-8**, it might provide a more comprehensive picture of mining locations in the Bear River Basin.
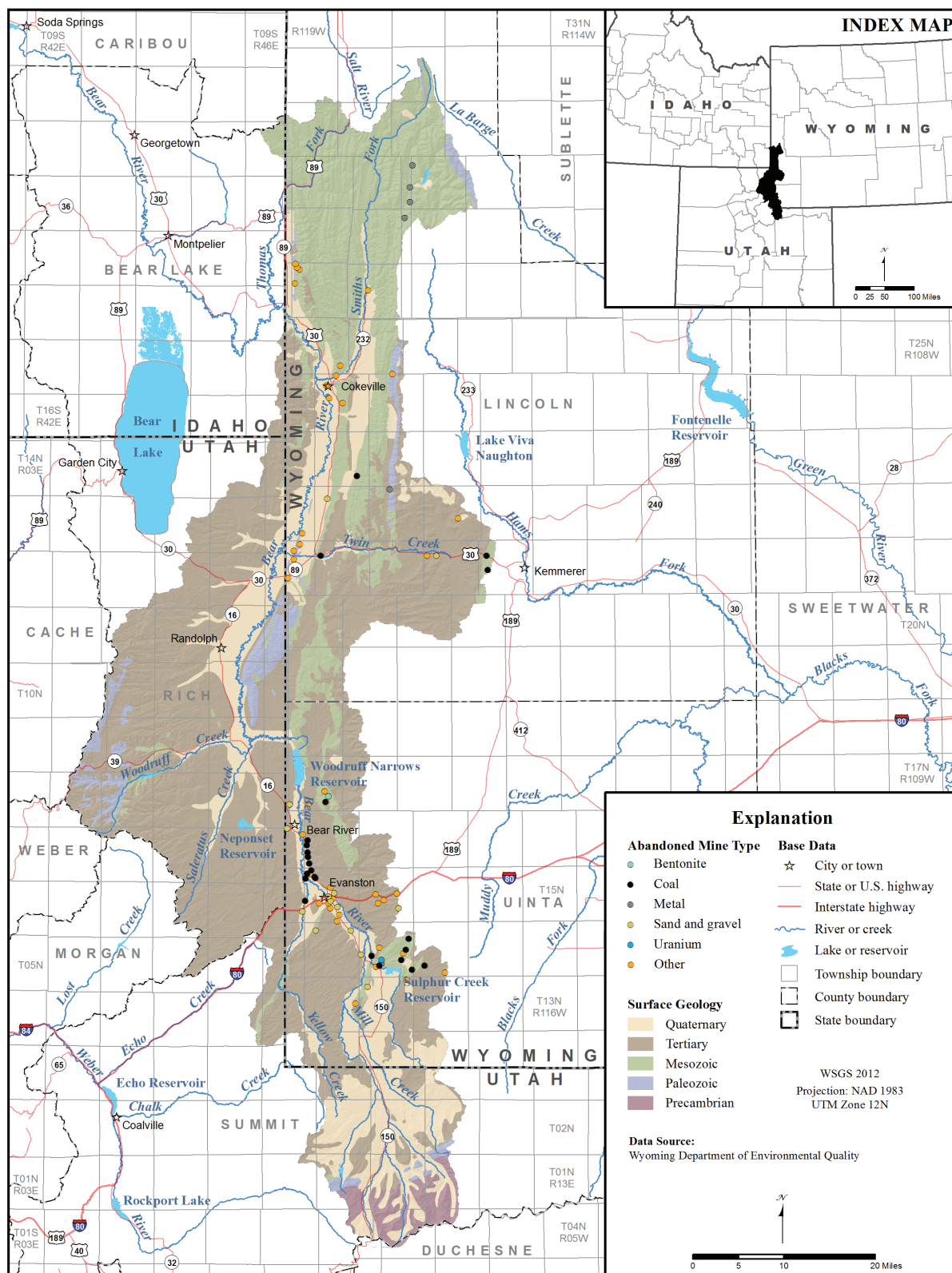
Figure 5-7. Potential groundwater contaminant sources: WDEQ Abandoned Mine Land Division abandoned mine sites, Bear River Basin, Wyoming.
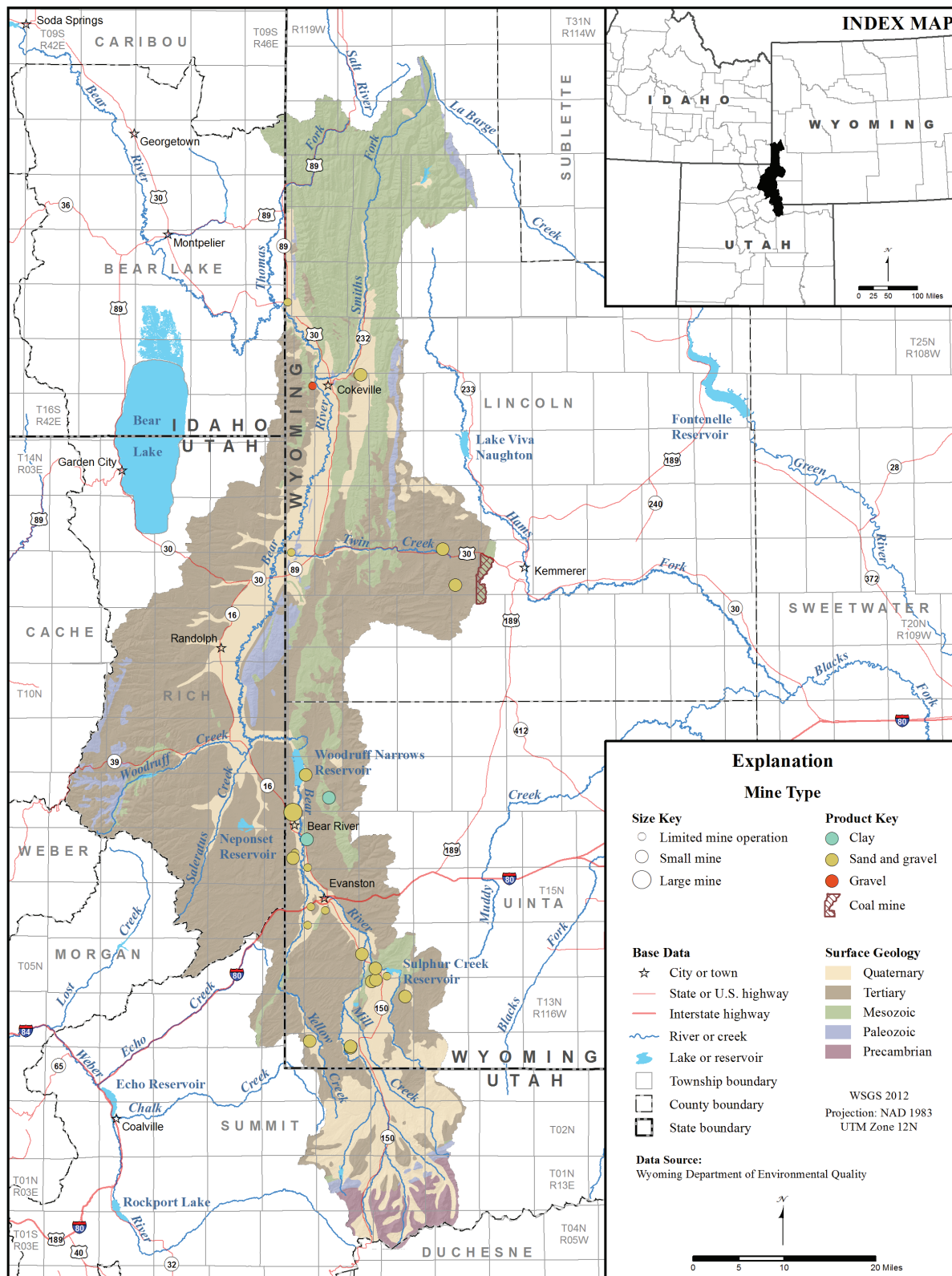
Figure 5-8. Potential groundwater contaminant sources: WDEQ Land Quality Division permitted mines, quarries and pits, Bear River Basin, Wyoming.
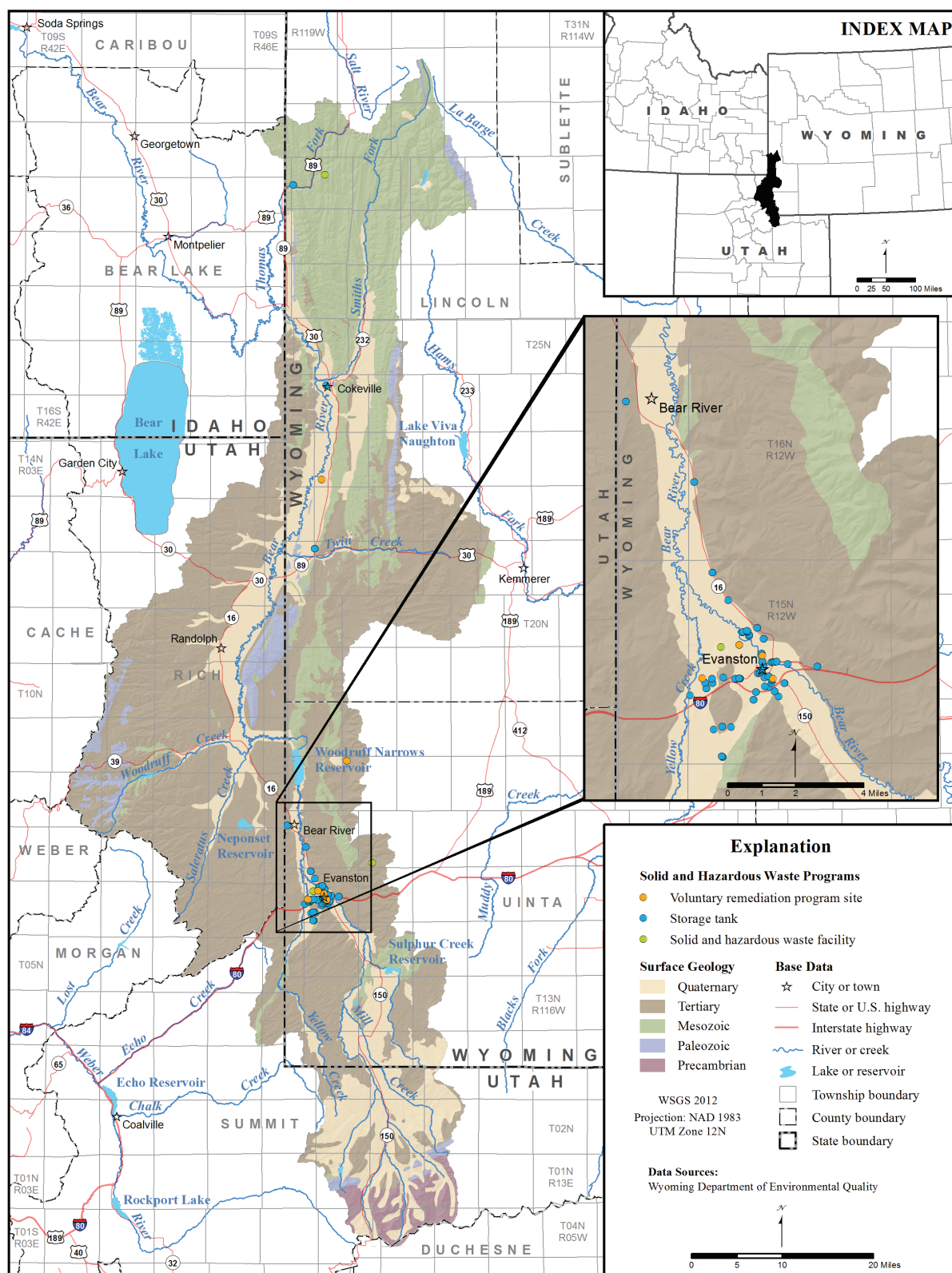
Figure 5-9. Potential groundwater contaminant sources: Wyoming State Geological Survey mapped mines, Bear River Basin, Wyoming, (locations from Harris, 2004).

Figure 5-10 - Volunteer Remediation Program (VRP) sites, storage tanks, solid and hazardous waste facilities - permitted by WDEQ Solid and Hazardous Waste Division (SHWD) including:

- Municipal landfills and transfer, treatment, and storage facilities;
- Industrial landfills, treatment, and storage facilities;
- Solid waste treatment, storage, and disposal facilities;
- Spill and hazardous waste corrective action sites;
- Illegal dump sites and historic site cleanups.

- **VRP Sites:** These are sites where soil or groundwater contamination is remediated by agreement between the SHWD and the responsible party under the Voluntary Remediation Program (VRP).

- **Active storage tanks:** In use or temporarily out of use, above- and underground storage tanks are regulated by the WDEQ/SHWD Storage Tank Program. Because releases can go undetected for long periods of time, underground storage tanks (USTs) have long been recognized for their potential to contaminate groundwater. The Storage Tank Program was developed, in large part, in response to the high number of releases from USTs.

- **Solid and hazardous waste facilities:** These contain a great number of potential contaminants in a variety of configurations. Wastes may be liquid, solid, or semisolid and stored either above or below ground in contained or uncontained repositories. Wastes are generally concentrated at these facilities, including concentrated liquid products that can leak from containers. Contaminants can migrate directly to shallow groundwater, or water from precipitation and other sources can infiltrate contaminant sources above the water table and form leachates composed of many contaminants. Active facilities usually store bulk contaminant products on-site (e.g., fuel, hazardous materials for recycling) that can also be sources of contamination if released.

5.6.3 Discussion

To be included in this study, location data for potential contaminant sources had to be in formats that could be imported into ARC/GIS databases. Some contaminant source types do not currently have the location data in the ARC/GIS format required for mapping, or the data exist but were unavailable. The following types of potential groundwater contaminant sources were not mapped in this study:

- Although a number of public owned treatment works (POTWs) and septic systems exist in the Bear River Basin, they were not mapped because adequate location data were not available. However, some large-capacity septic systems have been mapped as Class V injection facilities (**Fig. 5-5**).

- Areas where pesticides and herbicides are applied were not mapped for this study. The distribution of irrigated lands presented in the 2001 Bear River Basin Final. Report (States West Water Resources, 2001) shows the primary areas where agricultural chemicals would generally be applied in the Bear River Basin. In addition, recent USGS reports (Bartos and others, 2009; Eddy-Miller and Norris 2000; Eddy-Miller and Remley, 2004; Eddy-Miller and others, 2013) present the results of sampling to characterize pesticide occurrences in groundwater in areas determined by the earlier SDVC report (Hamerlinck and Arneson, 1998) to be most vulnerable to this type of contamination. The application of pesticides and herbicides is regulated by the WDEQ Nonpoint Source Program.
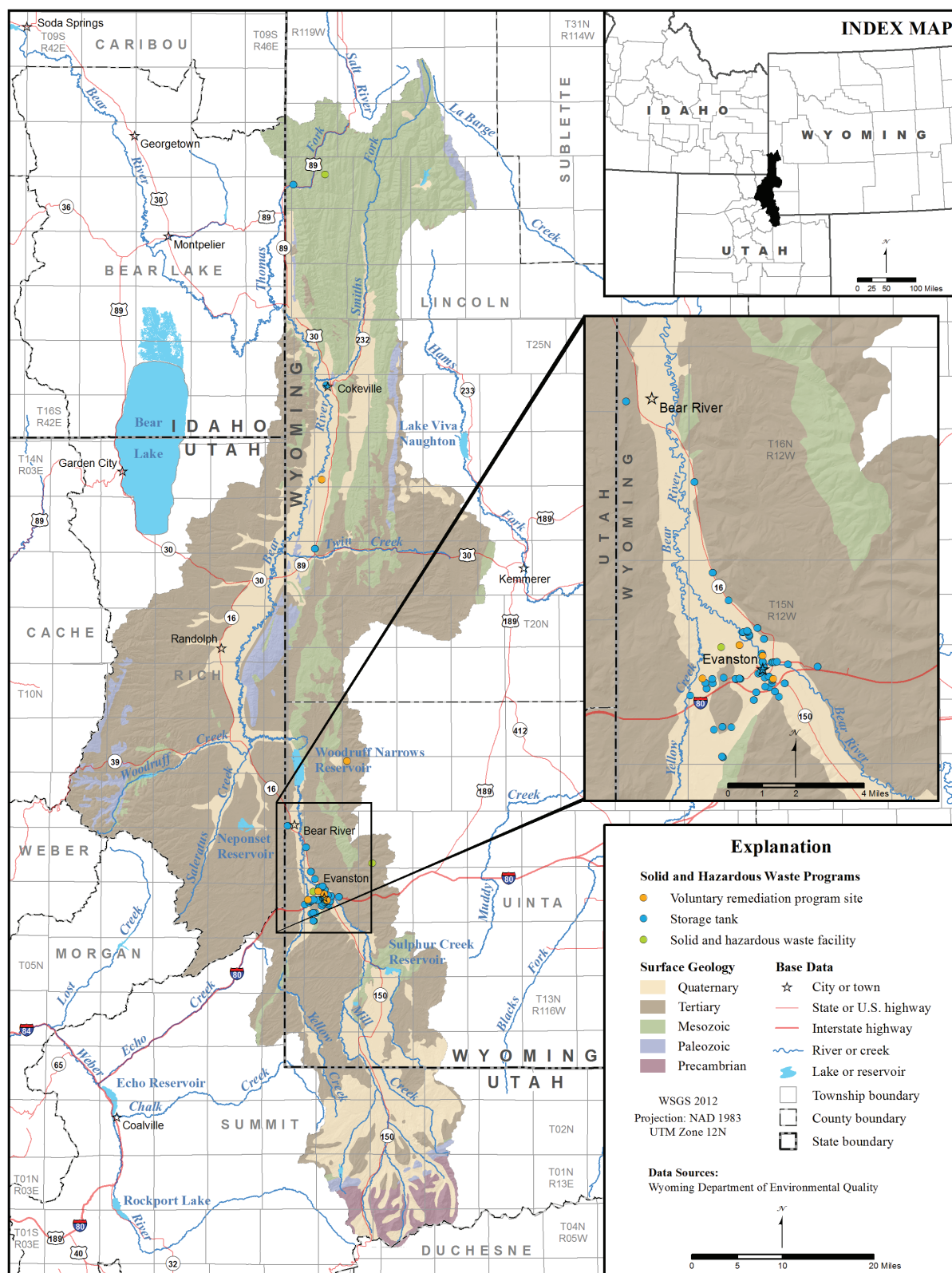
Figure 5-10. Potential groundwater contaminant sources: WDEQ permitted storage tanks, Voluntary Remediation Program (VRP), and permitted solid and hazardous waste facilities, Bear River Basin, Wyoming.

- There are currently no underground coal gasification (UCG) sites in the Bear River Basin.

- Produced water pits regulated by the WOGCC, oil and gas field, plants and compressor stations were not individually mapped for this study. These potential sources are located within the oil and gas fields mapped in **Figures 5-4** and **5-6**.

- Construction/demolition landfills, hazardous waste and used oil generators, used oil transporter and storage facilities, one-time disposal authorizations, mobile treatment units, de minimus spills, and complaints were included in the data received from SHWD but are not shown on **Figure 5-10** due to variable location (mobile) or relatively low potential for contaminating groundwater.

The above list and description of potential groundwater contaminant sources may be incomplete. This study may have overlooked additional potential sources associated with sufficient volumes of contaminants of concern. Pending identification of additional potential sources and improvements in data (particularly location information) for the potential sources that were identified but not mapped for this study, it may be possible to include them in the next update to the Bear River Basin Available Groundwater Determination Technical Memorandum.

5.6.4 Source Water Assessment, Wyoming Water Quality Monitoring, and associated groundwater protection programs

The federal government, under the Clean Water Act, recognized that states have primary responsibility for implementing programs to manage water quality. The primary objectives included under this broad responsibility are 1) establishing water quality standards, 2) monitoring

and assessing the quality of their waters, and 3) developing and implementing cleanup plans for waters that do not meets standards. To meet the water quality monitoring objective, WDEQ, the USGS Wyoming Water Science Center, and other agencies have developed a suite of cooperative and complementary groundwater assessment and monitoring programs:

- Source Water Assessment Program (SWAP)
- WDEQ Water Quality Monitoring Strategy, led to the development of the Statewide Ambient Groundwater Monitoring Program also known as the Wyoming Groundwater-Quality Monitoring Network
- The USGS Pesticide Monitoring Program in Wyoming

A general discussion of these programs follows. More information can be obtained from the WQD website at http://deq.state.wy.us/wqd/groundwater/index.asp under the Groundwater Assessment and Monitoring section.

The Source Water Assessment Program (SWAP)
The Source Water Assessment Program (SWAP), a component of the federal Safe Drinking Water Act enacted to help states protect both municipal and non-community public water systems (PWSs), provides additional information on potential local contaminant sources. The program, administered by the WDEQ Water Quality Division (WQD) and voluntary for the PWSs, includes the development of source-water assessments and protection plans, referred to as Wellhead Protection Plans (WHPs). The source-water assessment process includes: 1) determining the source-water contributing area, 2) generating an inventory of potential sources of contamination for each PWS, 3) determining the susceptibility of the PWS to identified potential contaminants, and 4) summarizing the information in a report. The development and implementation of SWAP/WHP assessments and plans is ongoing throughout Wyoming (**Fig. 5-11**). Additional information on the SWAP in Wyoming can be accessed at:

http://deq.state.wy.us/wqd/www/
SWPpercent20WHP/index.asp.

Copies of Source Water Assessment Reports for specific PWSs in the Bear River Basin can be accessed at: http://deq.state.wy.us/wqd/www/ SWPpercent20WHP/index.asp.

Water Quality Monitoring Strategy
Wyoming's strategy to develop an ambient groundwater quality database and a monitoring and assessment plan is designed to "determine the extent of groundwater contamination, update control strategies, and assess any needed changes in order to achieve groundwater protection goals" through a phased approach:

- Phase I – Aquifer prioritization (Bedessem and others, 2003; WyGISC, 2012)
- Phase II – Groundwater monitoring plan design (USGS, 2011)
- Phase III – Groundwater monitoring plan implementation and assessment
- Phase IV – Education and outreach for local groundwater protection efforts

Phase I – Aquifer prioritization
The aquifer prioritization process was a cooperative effort between the University of Wyoming, WDEQ, USGS Wyoming Water Science Center, Wyoming Geographic Information Science Center (WyGISC), and Wyoming State Geological Survey (WSGS) designed to develop a GIS based approach to determine critical areas within high use aquifers using available aquifer sensitivity (Hamerlinck and Arneson, 1998) and water and land use data. The goals of this process were to identify and rank the areas and aquifers that should be included in the statewide ambient groundwater monitoring plan, presenting the results in a series of maps. To do this, the project team included the following layers in the GIS model:

- Aquifer sensitivity map of Hamerlinck and Arneson (1998)
- High-use aquifers less than 500 feet below ground surface
- High-use aquifer sensitivity

- Current water use (domestic and municipal)
- Land use:
  - Coal bed methane wells
  - Rural residential development
  - Oil and gas exploration, development, and pipelines
  - Known and potential contaminant sources
  - Croplands and urban areas
  - Mining
  - Composite land uses (up to six uses)

Based on these analyses, the Aquifer Prioritization Map distinguishes four relative priority categories within high-use aquifer areas (low, low-moderate, moderate-high, and high). Bedessem and others (2003) contains complete descriptions of the methods used and subsequent results; the article is available online at the DEQ website: http://deq.state.wy.us/wqd/groundwater/ downloads/NGWApercent20Final.pdf. The map can be accessed online: http://deq.state.wy.us/wqd/ groundwater/downloads/map11.pdf.

Phases II and III – Groundwater monitoring plan design, implementation, and assessment
The groundwater monitoring plan was developed by the U.S. Geological Survey (USGS) and the Wyoming Department of Environmental Quality (DEQ) and instituted as the Wyoming Groundwater Quality Monitoring Network (WGQMN). The program is designed to monitor wells located in the priority areas and completed in the high use aquifers susceptible to contamination identified in Phase I.

Data collection and reporting by the USGS/ WDEQ include the following:
- Water level measurement
- Water sample collection and analysis for numerous natural and artificial constituents
- Stable isotope analysis in selected samples to determine the nature and extent of aquifer recharge
- Public access online reporting of water level and chemical analysis data at: (http://waterdata.usgs.gov/ wy/nwis/qw/)
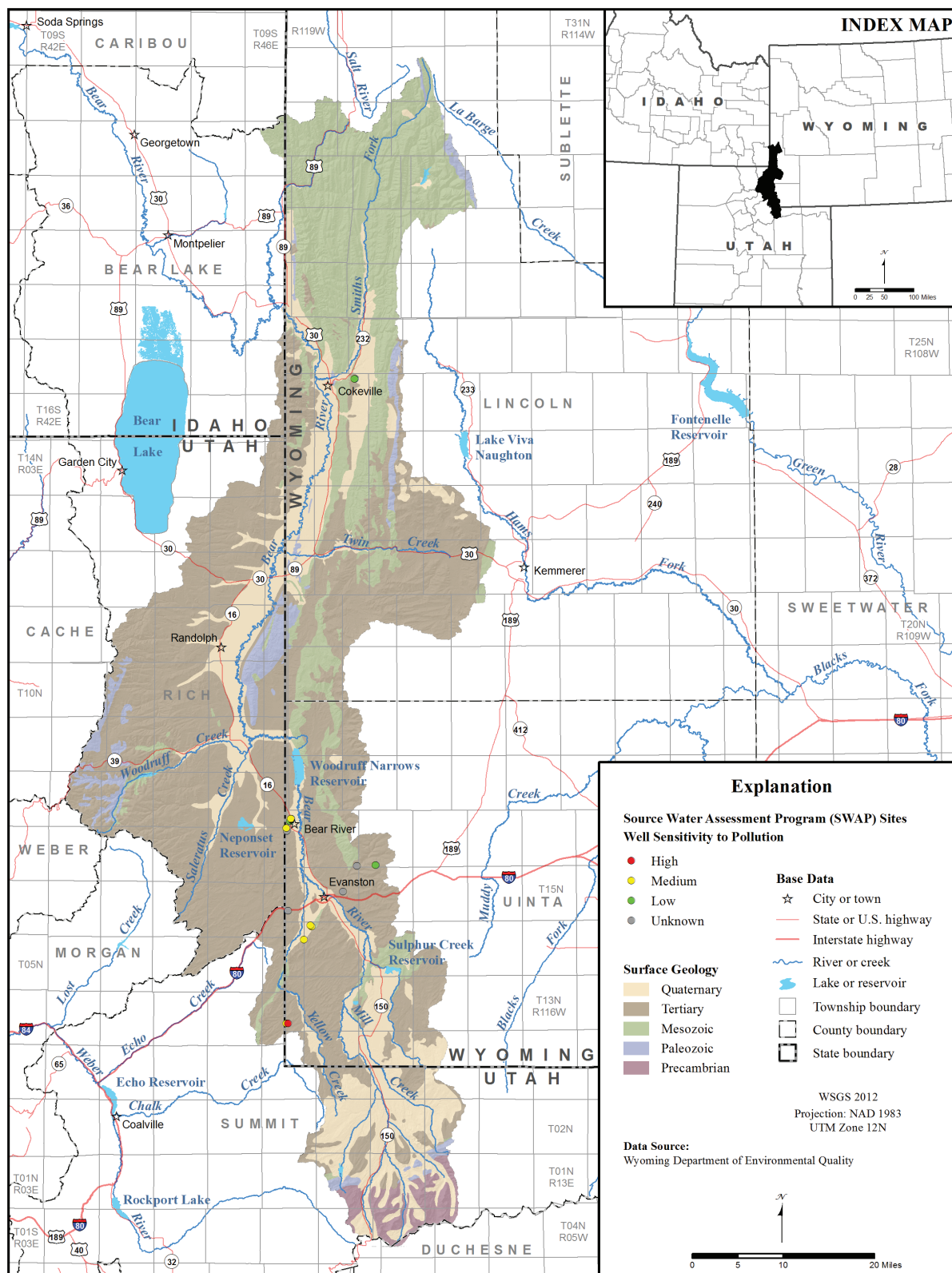
Figure 5-11. Surface Water Assessment and Protection, Bear River Basin, Wyoming.

- Periodic publication of summary groundwater data in USGS Fact Sheets and Scientific Investigations Reports

Program oversight is provided by a steering committee composed of representatives of the USGS, DEQ, U.S. Environmental Protection Agency (EPA), Wyoming Water Development Office, Wyoming State Geological Survey, and Wyoming State Engineer's Office. The steering committee meets periodically to evaluate program progress, and assess and modify program objectives.

Water quality analyses are conducted at the EPA Region 8 Laboratory in Denver, Colorado and other USGS laboratories. A complete description of the program and priority areas can be found online: http://pubs.usgs.gov/fs/2011/3041/.

Phase IV – Education and outreach for local groundwater protection efforts
The DEQ/WQD Groundwater Section provides extensive educational material and website links on its Web page: http://deq.state.wy.us/wqd/groundwater/index.asp.
Information on specific Wyoming aquifers can be found online at the Water Resources Data System Library: http://library.wrds.uwyo.edu/wwdcrept/wwdcrept.html, and in the USGS Publications website: http://pubs.er.usgs.gov/.

USGS Pesticide Monitoring Program in Wyoming
The USGS initiated a groundwater sampling program in 1995 to develop a baseline water quality dataset of pesticides in Wyoming aquifers. None of the 589 samples collected had pesticide levels exceeding the EPA Drinking Water Standards. The program is conducted in cooperation with DEQ and the Wyoming Department of Agriculture. Further program information and results are available online in USGS reports: http://pubs.er.usgs.gov/publication/fs03300; http://pubs.er.usgs.gov/publication/fs20043093;
http://pubs.usgs.gov/sir/2009/5024/; http://pubs.usgs.gov/fs/2009/3006/ and
http://pubs.er.usgs.gov/publication/fs20113011.

WDEQ Nonpoint Source Program
The goal of the Wyoming Nonpoint Source Program is to reduce the nonpoint source pollution to surface water and groundwater. The program directs efforts to reduce nonpoint source pollution, administers grants for pollution reduction efforts, and aids in watershed planning efforts. A 13 member steering committee, appointed by the Governor, provides program oversight and recommends water quality improvement projects for grant funding. More information about this program can be obtained online: http://deq.state.wy.us/wqd/watershed/nps/NPS.htm.

All three programs address the common goal of to protect Wyoming's groundwater resources and inventory potential sources of contamination. The programs can be mutually beneficial by working together and including relevant information, either directly or by reference, to supplement their databases. Organizing as much groundwater quality and hydrogeologic information into an evolving master database would be useful in protecting and sustainably developing groundwater resources throughout Wyoming.

Chapter 6
Bear River Basin Hydrogeology and Groundwater Resources

Karl Taboga and Paul Taucher

Wyoming's groundwater resources occur in both unconsolidated deposits and bedrock formations. In terms of frequency of use, the primary hydrogeologic unit in the Bear River Basin is the Quaternary Bear River alluvium (WWDO, 2012) (**Figs. 8-1** through **8-4; Pl. 6**). Additionally, over twenty bedrock aquifers, ranging in geologic age from Paleozoic to Tertiary (**Pls. 2** and **5**), exhibit heterogeneous permeability and provide variable amounts of useable groundwater.

Generally, aquifers are defined as geological units that store and transport useable amounts of groundwater while less permeable, confining units impede groundwater flow (**Section 5.1.1**). In practice, the distinction between aquifers and confining units is not so clear. A geologic unit that has been classified as confining at one location may act as an aquifer at another. Virtually all of the geologic units in the Bear River Basin, including confining units, are capable of yielding at least small quantities of groundwater. For example, the Green River Formation is classified as both an aquifer and a confining unit in the Bear River Basin, and several springs discharge water from this formation at the surface (**Pl. 3**). Permeability can vary widely within an individual geologic unit depending on its lithology and the geologic structure present. Carbonate aquifers, such as the Thaynes Limestone, commonly exhibit the highest yields in areas where secondary permeability (e.g., solution openings, bedding plane partings, and fractures) has developed. The great differences in permeability between and within geologic units account, in part, for the observed variation in the available quantity and the quality of a basin's groundwater resources.

One of the primary purposes of this study is to evaluate the groundwater resource of the Bear River Basin primarily through the following tasks (**Chapter 1**):

- Estimate the quantity of water in the aquifers
- Describe the aquifer recharge areas
- Estimate aquifer recharge rates

- Estimate the "safe yield" potential for the aquifers

Although an enormous quantity of groundwater is stored in the Bear River groundwater basin, the basin's complex geology does not permit the use of the general assumptions regarding aquifer geometry, saturated thickness, and hydraulic properties. Hydrogeologists commonly employ these assumptions to calculate a plausible estimate of total and producible groundwater resources. The data required for a basin-wide, aquifer-specific assessment of groundwater resources is not available and is unlikely to ever be developed. Therefore, groundwater resources evaluated in this study rely on previous estimates (Hamerlinck and Arneson, 1998) of the percentage of precipitation in areas where aquifer units outcrop that will ultimately reach the subsurface as recharge (**Figs. 6-1** through **6-4**) and the formulation of a basin-wide water balance (**Chapter 8**). The technical and conceptual issues concerning recharge are discussed in **Section 5.1.3**.

Similarly, the extensive hydrogeologic data required to estimate the safe yield of groundwater for the entirety of the Bear River Basin does not exist. Furthermore, geoscience has evolved beyond the concept of safe yield since it was first introduced by Lee (1915), and many scientists and water managers have largely abandoned this principle in favor of concepts such as sustainable development. The recharge volumes estimated in this chapter provide a first step to evaluating sustained yields for the basin's hydrologic units. The historical development of the safe yield concept and its technical context is discussed in **Section 5.1.4**.

6.1 Hydrostratigraphy and recharge to aquifer outcrop areas

To begin the process of evaluating recharge, specific aquifers and groups of aquifers to which the recharge calculations will be applied must be distinguished (**Figs. 6-1** through **6-4**). Several previous studies (**Section 2.1**) have grouped the Bear River Basin's hydrogeologic units into various combinations of aquifers, aquifer systems, and confining units. The hydrostratigraphy

developed for this study is based on previous regional assessments and is summarized in the hydrogeology map illustrated in **Plate 2** in the hydrostratigraphic charts shown on **Plate 5**, and in **Chapter 7**. The hydrostratigraphic charts in **Plate 5** detail the hydrogeologic nomenclature used in previous studies, including the aquifer classification system from the Statewide Framework Water Plan (WWC Engineering and others, 2007). **Appendix A** describes the geologic units used to develop the surface hydrogeology shown on **Plate 2**.

Section 5.2 discusses how the map units of Love and Christiansen (1985), previously compiled into a Geographic Information Systems (GIS) database by the U.S. Geological Survey (USGS) and Wyoming State Geological Survey (WSGS), were used to develop **Plate 2**. Love and Christiansen (1985), however, were not able to distinguish all stratigraphic units present in the Bear River Basin due to the sheer size of the dataset and cartographic limitations. Therefore, some geologic units were not mapped individually but instead, are shown on **Plate 2** as undifferentiated hydrogeologic units. To address this deficit, the outcrops of hydrogeologic units that were assigned as aquifers or aquifer groups (**Pl. 2**) are aggregated by geologic age (**Pl. 2**). These aggregated aquifers, or aquifer recharge zones, were generated as GIS shapefiles and used to calculate recharge volumes and rates:

- Quaternary aquifers (**Fig. 6-1**)
- Tertiary aquifers (**Fig. 6-2**)
- Mesozoic aquifers (**Fig. 6-3**)
- Paleozoic aquifers (**Fig. 6-4**)

Precambrian formations, buried more than 25,000 feet below the surface in the Wyoming portion of the Bear River Basin consist primarily of quartzite, gneiss, and schist (Royce, 1993). These units function as a regional confining unit and do not contribute to groundwater supplies.

6.2 Average annual recharge

Only a fraction of the groundwater stored in the Bear River Basin can be withdrawn for beneficial use because groundwater naturally discharges to streams, springs, lakes, and wetlands

and is further lost through evapotranspiration. Under natural conditions, a state of dynamic equilibrium in which natural discharges to surface waters and evapotranspiration are counterbalanced by recharge exists. In effect, this balance means that higher rates of recharge result in higher levels of natural discharge over time. Withdrawals from wells and springs remove groundwater from aquifer storage and natural discharges. Thus, without careful management, over time flows in springs, streams, and wetlands, as well as aquifer storage, will be depleted to such a degree that water rights holders will not receive their full appropriation and riparian ecosystems will collapse. This risk has long been recognized by Wyoming's agricultural community, as well as water managers for municipalities and conservation districts, state water administrators, and legislators. The connection between surface water and groundwater resources has been incorporated into Wyoming's water law and also forms one of the core tenets in forming Wyoming's interstate water compacts, including the Bear River Compact (**Appendix D**).

To evaluate recharge on a regional scale, this study combines estimated, average annual recharge data from the Spatial Data and Visualization Center (SDVC) (Hamerlinck and Arneson, 1998) and WSGS maps illustrating where pertinent hydrogeologic units outcrop in the Bear River Basin (**Pl. 2; Figs. 6-1** through **6-4**). As with the original SDVC study (Hamerlinck and Arneson, 1998), this report does not consider artificial recharge from lawn and crop irrigation, surface water diversions and flow between aquifers in poorly completed wells. It should be noted; however, that artificial recharge, particularly from crop irrigation and irrigation diversion structures, may be substantial in the alluvial aquifers of the Bear River Basin (Forsgren and Associates, 2001; WWDO, 2012).

Withdrawal and consumptive use data from the 2011 Bear River Basin Report (WWDO, 2012 page 44, Tables 5-4 and 5-5) indicate that approximately 8,000 acre–feet of irrigation water returns to the watershed in the form of recharge or as direct return flows to streams. Currently, it is not possible to quantify the amounts that recharge
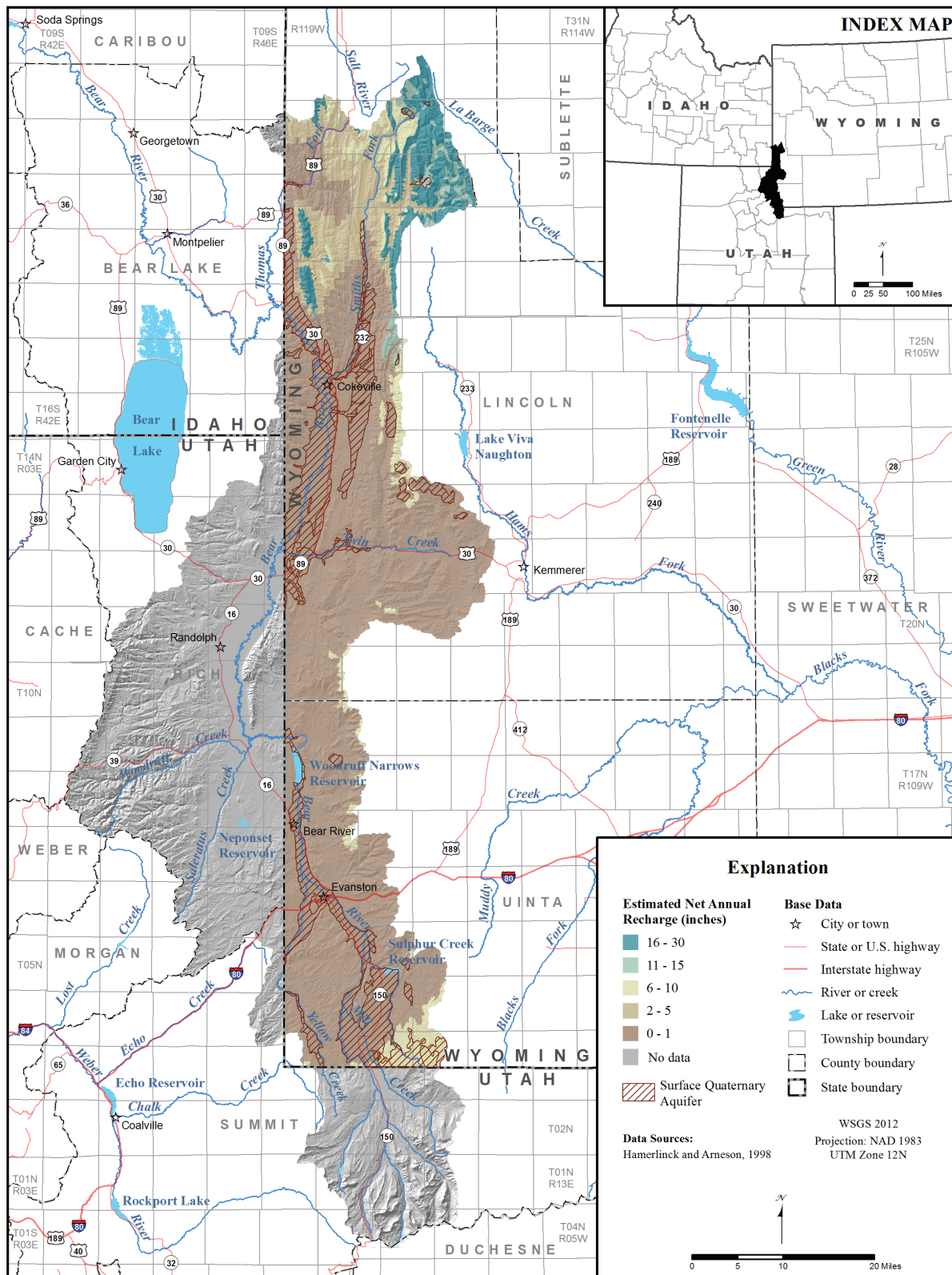
Figure 6-1. Estimated net annual aquifer recharge – surface Quaternary aquifer, Bear River Basin, Wyoming.
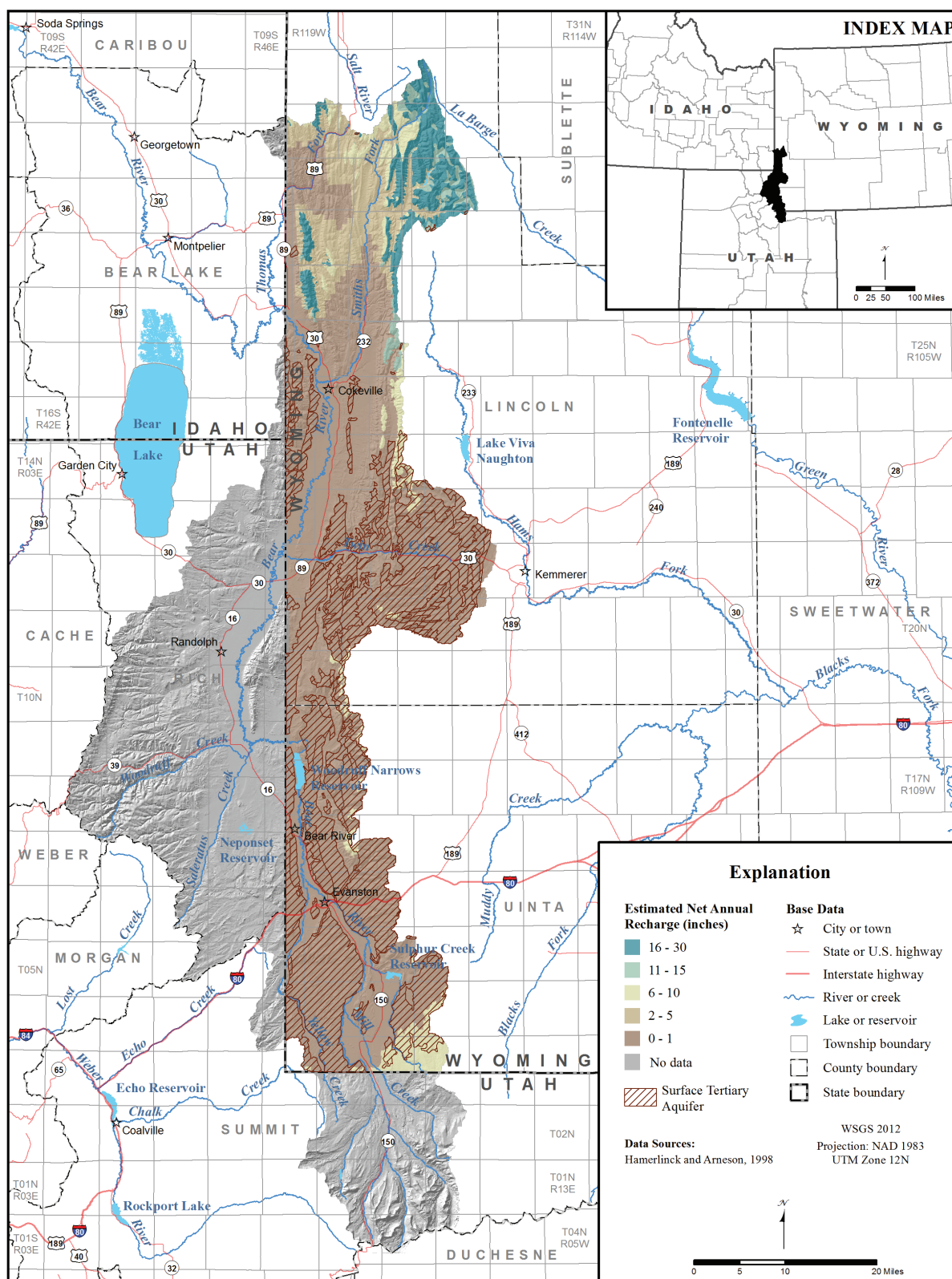
Figure 6-2. Estimated net annual aquifer recharge – surface Tertiary aquifer, Bear River Basin, Wyoming.
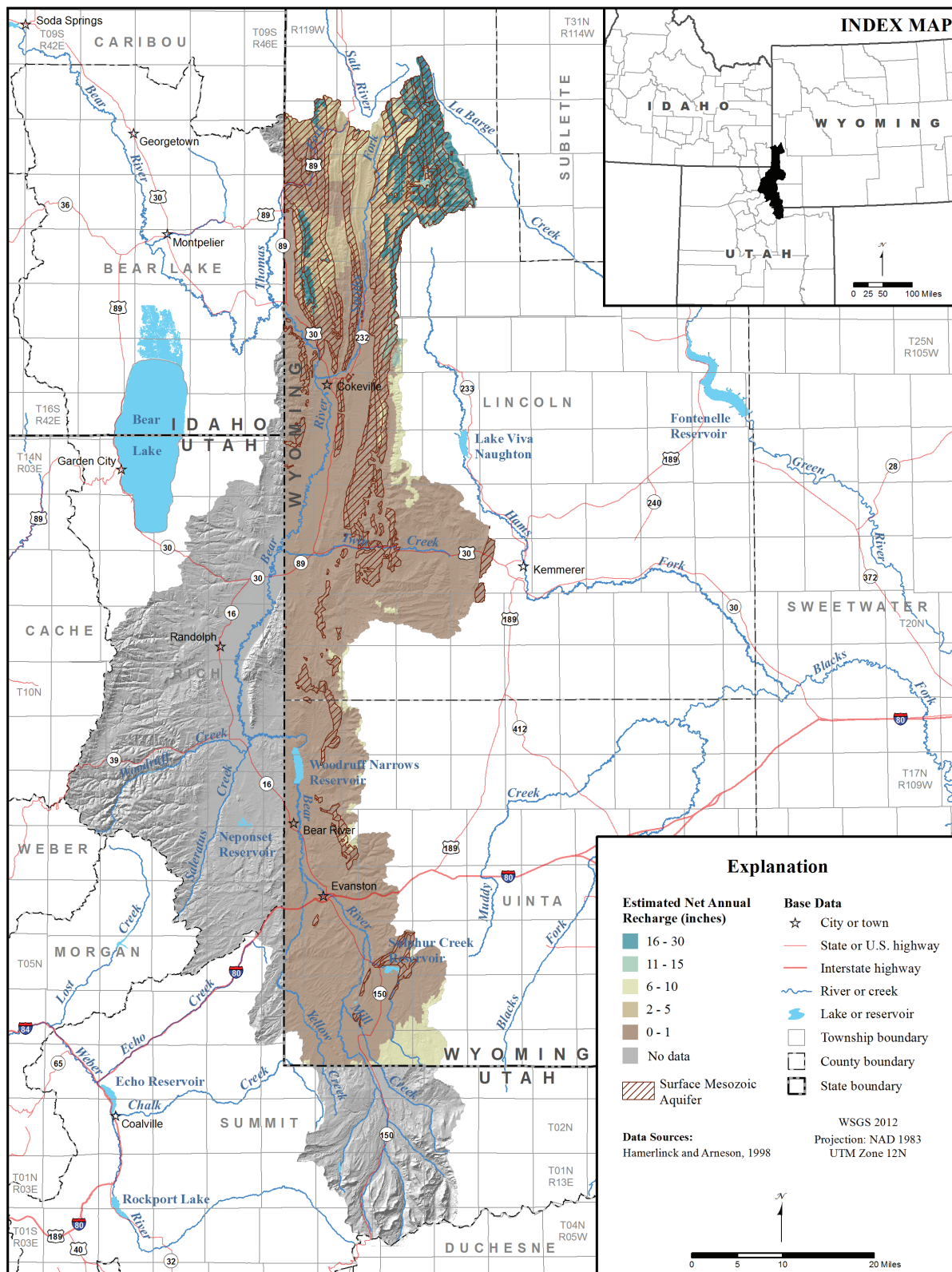
Figure 6-3. Estimated net annual aquifer recharge – surface Mesozoic aquifer, Bear River Basin, Wyoming.
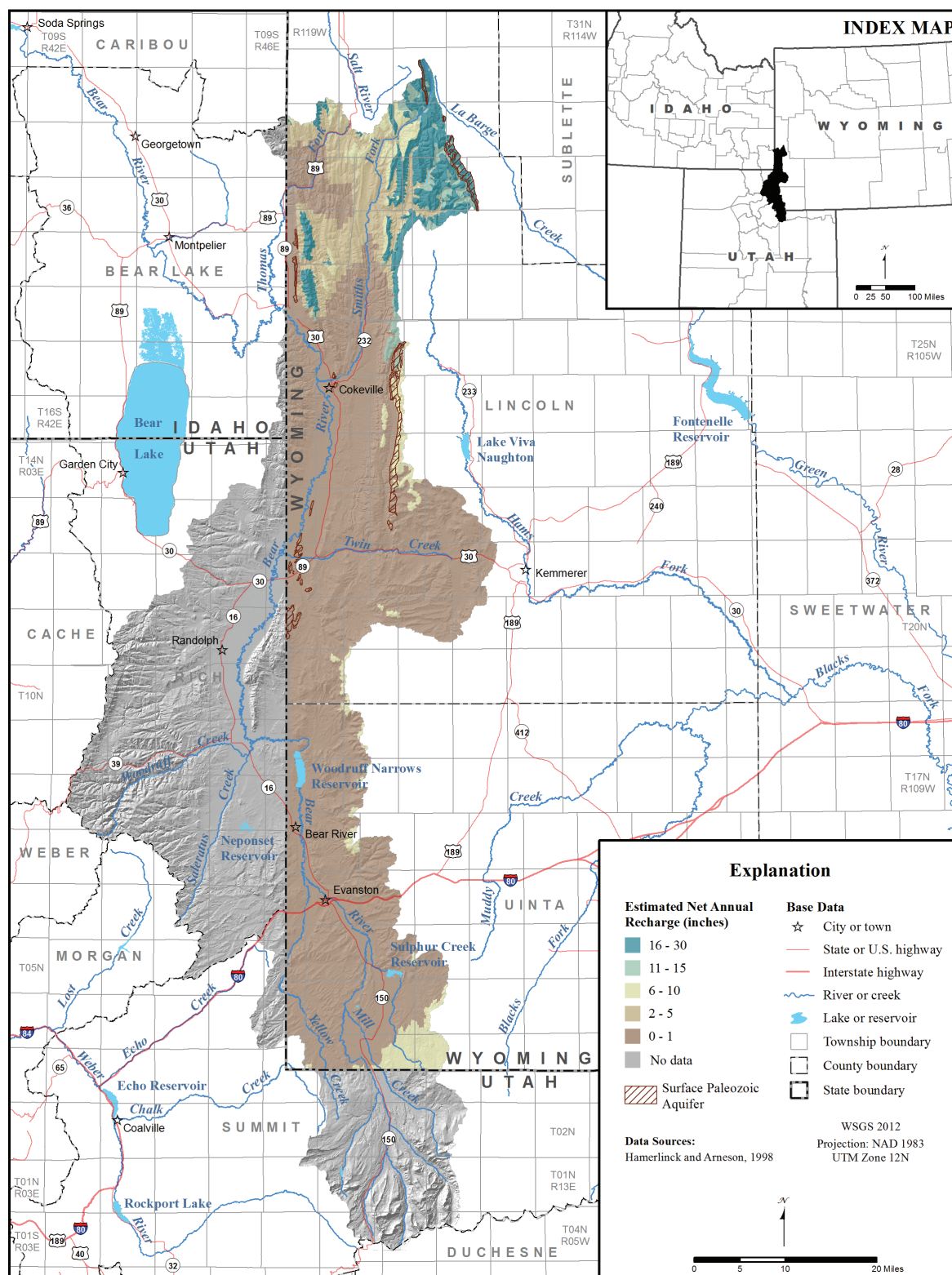
Figure 6-4. Estimated net annual aquifer recharge – surface Paleozoic aquifer, Bear River Basin, Wyoming.

underlying aquifers as opposed to those that return as direct surface flows. Furthermore, it is likely that a substantial portion of artificial recharge from irrigation becomes baseflow to the Bear River and its tributaries because most irrigated lands overlie alluvial deposits (Tab E, Figure 1 - Forsgren and Associates, 2001). The potentiometric surface map shown on **Plate 6** of this report indicates that groundwater flows to gaining reaches along much of the Bear River mainstem.

Even so, average annual recharge constrained by best estimates of annual discharge (both natural and by pumping) and periodic water level monitoring provide valuable baseline data. These data assist in establishing benchmarks for sustained yield, namely the volume of water that can be artificially discharged without unacceptably depleting aquifer storage or natural discharges. While aquifer-specific recharge can be reasonably estimated, aquifer-specific discharges are difficult to constrain. Estimates of annual groundwater withdrawals and consumptive uses from the previous Bear River Basin water plans (Forsgren and Associates, 2001; WWDO, 2012) and the Statewide Framework Water Plan (WWC Engineering and others, 2007) are discussed in **Chapter 8**.

Estimated, average annual, recharge (**Fig. 5-2**) in the Wyoming portion of the Bear River Basin ranges from less than one inch per year in the basin interior to over thirty inches per year in the surrounding mountains (Hamerlinck and Arneson, 1998). Mountains and foothills receive more recharge than basin lowlands due to environmental attributes characteristic of highland zones:

- Greater amounts of precipitation and more persistent snow pack (**Fig. 3-3**)
- More abundant vegetation
- Soil and vegetation combinations more favorable to infiltration
- Lower rates of evapotranspiration
- Better exposure of the upturned and weathered edges of hydrogeologic units facilitates infiltration because zones of higher permeability often parallel bedding
- The presence of structural features that

enhance recharge (e.g., faults, fractures, joints, fault/fracture-controlled surface drainages)

Figure 6-5 shows how recharge efficiency, defined as a percentage of average annual precipitation (R/P), varies throughout the Wyoming portion of the Bear River Basin and suggests what environmental factors exert control on recharge. Recharge is most efficient in the mountains of the Tunp, Sublette, and Wyoming ranges and the foothills of the High Uinta Mountains, but recharge rates are also slightly higher west and southwest of Evanston. The dataset for **Figure 6-5** was generated by dividing 4,000-meter grid cells and assigning values for average annual aquifer recharge (**Fig. 5-1**) and average annual precipitation (**Fig. 3-3**) to each cell; both data sets were obtained from the SDVC aquifer vulnerability study prepared for the State of Wyoming (Hamerlinck and Arneson, 1998).

Average annual recharge (**Fig. 5-2**) is based on percolation percentages for different soil/vegetation combinations multiplied by average annual precipitation for the 30-year period from 1981 to 2010. Total average annual precipitation has been estimated (PRISM, 2013) as 2,640,125 acre-feet for the larger Bear River Basin shown in Figure 3-3 and 1,398,194 acre-feet for the Wyoming portion exclusively (**Table 8-2a**). Although this approach does not fully consider all factors that affect recharge, initial infiltration and precipitation levels are probably the most important factors on a regional scale. Consideration of the other factors listed above and in **Section 5.1.3.1** should confirm the general pattern of recharge efficiency displayed in **Figure 6-5**. However, as discussed previously (**Sections 5.1.3.1** and **5.4**), local recharge rates may be dominated by site-specific hydrogeologic conditions (e.g., solution-enhanced fracture permeability). Lastly, Hamerlinck and Arneson (1998) indicated that many areas in the basin interior receive zero or, in some cases, negative amounts of recharge. In this report these areas were treated as receiving zero recharge; negative values were not subtracted from the total.

Table 6-1 shows the percentage of surface area by

Table 6-1. Percent of aquifer recharge zones recharging at varying efficiencies.

Recharge Efficiency as annual recharge / annual precipitation, (in percent)	0-1	2	5	6	10	30	35	60
Quaternary	57.61	0.00	27.37	7.09	0.00	0.00	7.53	0.39
Tertiary	17.29	8.68	0.93	67.94	0.06	0.00	5.07	0.03
Mesozoic	25.97	0.00	0.38	41.48	0.28	5.71	4.28	21.89
Paleozoic	37.56	0.00	0.46	10.64	-	-	21.71	29.63

specified range of recharge efficiency, as R/P and as determined via GIS analysis, for each of the four, age-classified, aquifer recharge zones (**Figs. 6-1** through **6-4; Pl. 2**).

Table 6-1 shows that most recharge to all aquifer recharge zones in the Bear River Basin occurs at the lowest range of recharge efficiency (0-10 percent of precipitation). Higher proportions of Mesozoic and Paleozoic aquifers receive recharge at efficiencies greater than 10 percent, likely due to the elevation of older aquifers exposed in upland areas. The consistently low recharge efficiencies calculated for Tertiary and Quaternary aquifer zones may reflect the subdued relief and aridity (**Fig. 3-3**) within the interior of the Bear River Basin.

Recharge volumes for the established aquifer recharge areas were calculated with the following, general equation:

$$\text{Average annual recharge volume (acre-feet)} = \text{Aquifer recharge area (acres)} \times \text{Average annual recharge (feet)}$$

The outcrop areas assigned to aquifer groups in the recharge calculations (**Figs. 6-1** through **6-4**) were determined from the hydrogeologic map (**Pl. 2**) developed for this study. Average annual rates of recharge throughout the Bear River Basin (mapped in 100-meter cells) adapted from the Wyoming Groundwater Vulnerability Assessment Handbook (Hamerlinck and Arneson, 1998) are shown in **Figure 5-1**. Recharge rates were grouped into the five ranges to make **Figure 5-1** more readable

and to mitigate the uncertainties associated with the recharge calculations. Recharge rates for the aquifer recharge zones, mapped as polygons, were converted from inches to feet, and the average annual recharge volumes (in acre-feet) were calculated using the equation above.

These recharge calculations do not incorporate confining unit outcrop areas (**Pl. 2**). As noted in **Section 5.2**, undifferentiated geologic units were included in the established aquifer recharge areas of the same age. Recharge calculations that exclude confining-unit outcrop areas provide a more conservative estimate of available groundwater resources. Furthermore, leakage from adjacent confining layers was also disregarded in this evaluation.

Table 6-2 summarizes calculated recharge for the Bear River Basin over the ranges of average annual recharge mapped on **Figure 5-2** and the aquifer recharge zones displayed in **Figures 6-1** through **6-4**. A "best total" amount for each range of recharge over the outcrop area of each aquifer group is provided in **Tables 6-2** and **6-3** based on the recharge area for each whole inch of recharge in the database compiled for this study. "Best total" is calculated directly from the detailed cell-by-cell recharge data and the corresponding surface area.

Table 6-3 summarizes calculated, average annual recharge statistics from the more detailed calculations provided in **Table 6-2**. Additionally, **Table 6-3** provides a "best total," average recharge depth, delivered over the entire surface area of
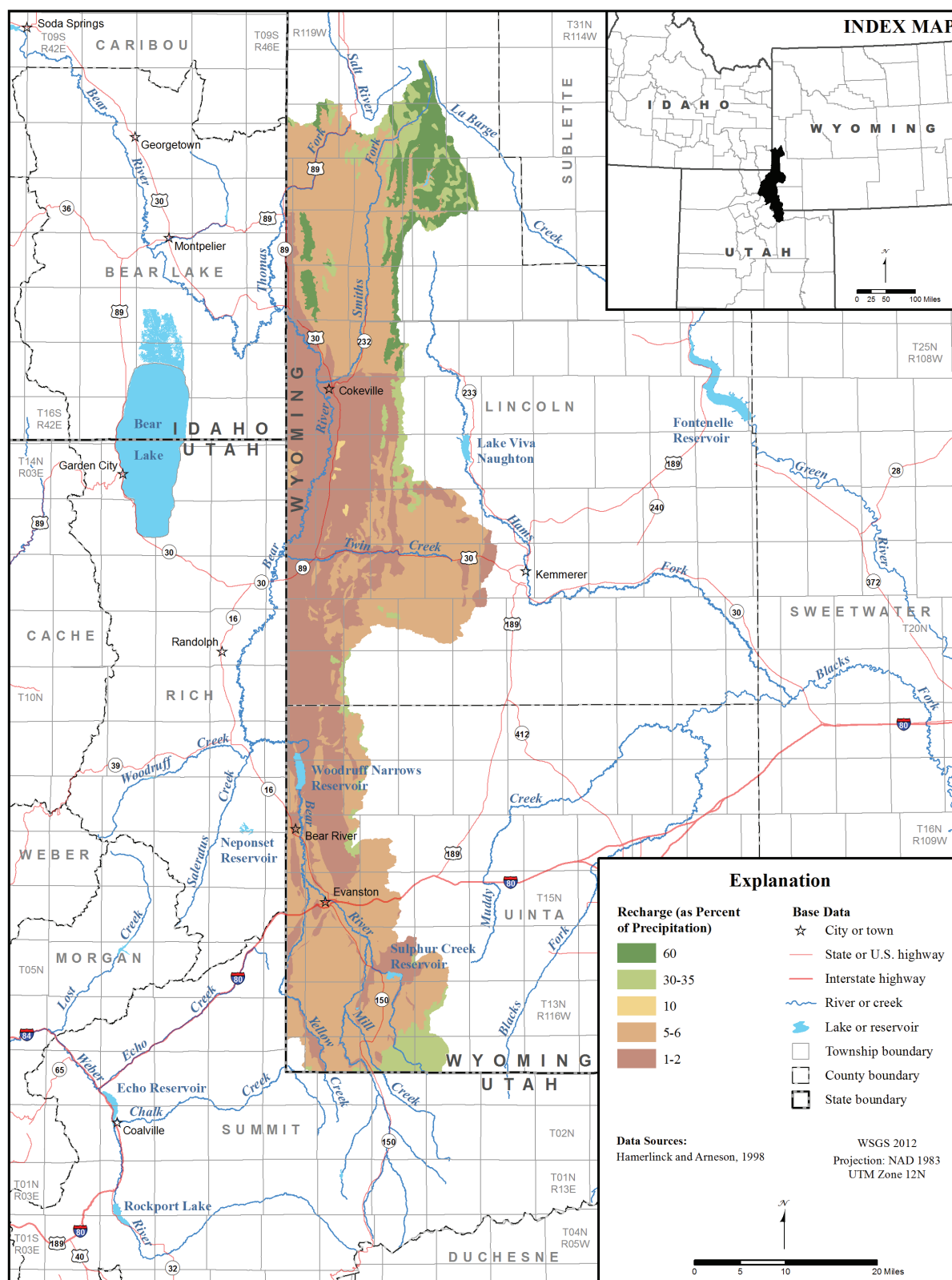
Figure 6-5. Aquifer recharge as percentage of precipitation using 1981 - 2010 precipitation normals, Bear River Basin, Wyoming.

Table 6-2. Bear River Basin average annual recharge calculations

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Average Annual Recharge
	Inches	Feet	Acres	Best Total (Acre-feet)
Quaternary	0	0.00	107,991	0
	1	0.08	48,565	4,111
	5	0.42		
	6	0.50	12,100	8,191
	10	0.83		
	11	0.92	862	868
	15	1.25		
	16	1.33	515	885
	25	2.08		
	TOTAL		170,033	14,055

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Range - Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Mesozoic	0	0.00	67,916	0
	1	0.08	110,286	13,754
	5	0.42		
	6	0.50	16,839	12,535
	10	0.83		
	11	0.92	12,566	13,510
	15	1.25		
	16	1.33	53,700	88,229
	29	2.42		
	TOTAL		261,307	128,029

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Tertiary	0	0.00	105,624	0
	1	0.08	273,508	22,921
	5	0.42		
	6	0.50	19,628	11,611
	10	0.83		
	11	0.92	267	261
	15	1.25		
	16	1.33	93	148
	28	2.33		
	TOTAL		399,120	34,940

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Range - Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Paleozoic	0	0.00	6,613	0
	1	0.08	2,153	650
	5	0.42		
	6	0.50	2,520	1,331
	10	0.83		
	11	0.92	1,548	1,651
	15	1.25		
	16	1.33	4,053	8,312
	37	3.08		
	Low TOTAL		16,886	11,944

Bear River Basin TOTAL 847,246 188,968

[1] adapted from Hamerlinck and Arneson, 1998 and [2] PRISM, 2013

Table 6-3. Annual recharge statistics for Bear River Basin aquifer recharge zones.

Aquifer Recharge Zone	Recharge zone surface area (acres)	Percent of total basin surface area	"Best total" annual recharge volume (acre-feet)	"Best total" recharge as percent of basin total	"Best total" average recharge depth, in	
					feet	inches
Quaternary	170,033	20.07%	14,055	7.44%	0.083	1.0
Tertiary	399,120	47.10%	34,940	18.49%	0.088	1.1
Mesozoic	261,307	30.84%	128,029	67.75%	0.490	5.9
Paleozoic	16,886	1.99%	11,944	6.32%	0.707	8.5
Total, Paleozoic through Quaternary zones	**847,346**	**100.00%**	**188,968**	**100.00%**	**0.223**	**2.7**

each aquifer recharge zone. An analysis of average recharge depths shows that high elevation Paleozoic aquifers receive 0.707 feet (8.5 inches) of recharge compared to about 1 inch in Quaternary and Tertiary aquifers. The Mesozoic aquifers, which crop out in highland areas located primarily in northern and central parts of the basin (Pl. 2), receive 0.49 feet (~5.9 inches) of recharge. Coupled with the fact that they are also areally extensive, covering about 31 percent of the basin's surface area, infiltration through Mesozoic strata provides about 68 percent of the basin's recharge.

Table 6-2 illustrates that, predictably, recharge volume percentages are generally consistent with the surface areas of the aquifer recharge zones. Although the Tertiary aquifers (**Fig. 6-2**) constitute the largest aquifer recharge area *(over 624 square miles)*, they receive the second largest volume (39,341 acre ft/year) of recharge. The Mesozoic group (**Fig. 6-3**) outcrops over 408 square miles but receives the highest amounts of annual recharge (130,858 acre-ft/year). Quaternary aquifers (**Fig. 6-1**) receive 18,554 acre-ft of recharge annually. The Paleozoic aquifers (**Fig. 6-4**) constitute the

smallest aquifer recharge area (26 square miles) and receive the smallest recharge volume (11,944 acre-ft/year) in the Bear River Basin.

In the Wyoming part of the Bear River Basin, the best estimate of total recharge is 188,968 acre- feet, or 13.5 percent, of total precipitation. Notably, this value approaches the "rule-of-thumb" frequently cited by water resource professionals: approximately ten percent of precipitation will eventually become recharge. Finally, the volumes of recharge that enter groundwater storage are further reduced in areas where recharge is "rejected" or discharged as spring flow. Once rejected, it may be evaporated, beneficially used or discharged as streamflow.

6.3 Summary

- Recharge is ultimately controlled by precipitation. Total average annual precipitation for the tri-state Bear River Basin (**Fig. 3-2**) has been estimated as 2,640,125 acre-feet and 1,398,194 acre-feet for the Wyoming portion of the basin (**Table 8-2a**).

- Recharge controlled by precipitation and soil/vegetation combinations in the Wyoming portion of the Bear River Basin ranges from 0 to 37 inches (Hamerlinck and Arneson, 1998), with the lowest values occurring in the interior basins and the highest values in the surrounding mountain ranges.

- Recharge efficiency (recharge as a percentage of precipitation, or R/P) varies based on the factors used the Wyoming Groundwater Vulnerability Assessment Handbook (Hamerlinck and Arneson, 1998) to estimate recharge throughout Wyoming.

- Other factors controlling recharge may dominate locally (e.g., solution enhanced fractures); however, consideration of these factors should confirm the overall pattern of recharge and recharge efficiency.

- Recharge from precipitation to flat-lying Tertiary and Quaternary aquifers in the interior basin is generally less efficient than recharge to the upturned Mesozoic and Paleozoic aquifers in the uplifted and mountainous areas. Recharge in the Bear River Basin is most efficient in higher mountain, Paleozoic terrains.

- Recharge to Precambrian formations was not evaluated because, considered together, these units act as a regional confining unit. Because Precambrian rocks are buried deeply below younger sedimentary formations, they do not supply groundwater in the Bear River Basin.

- Estimates of average annual recharge in the Bear River Basin are presented as a "best total" based on the cell-by-cell product of area and rate of recharge.

Chapter 7

Physical and chemical characteristics of hydrogeologic units in the Bear River Basin

Timothy T. Bartos, Keith E. Clarey, Laura L. Hallberg and Melanie L. Clark

In this report, previously published data describing the physical characteristics of hydrogeologic units (aquifers and confining units) are presented on a map (**Pl. 3**) and summarized in tabular format (**Pl. 4**). The original sources of the data used to construct the summary are listed (see the bottom of **Pl. 4**). Physical characteristics are summarized to provide a broad summary of hydrogeologic unit characteristics and include spring discharge, well yields, specific capacity, transmissivity, porosity, hydraulic conductivity, and storage (storativity/storage coefficient). Individual data values and corresponding interpretation were utilized and summarized as presented in the original reports—no reinterpretation of existing hydraulic data was conducted for this study. For example, values of transmissivity derived from aquifer tests were used as published in the original reports, and no reanalysis of previously published aquifer tests was conducted.

7.1 Bear River Basin

The physical and chemical characteristics of hydrogeologic units of Cenozoic, Mesozoic, Paleozoic, and Precambrian age in the Bear River Basin (Bear River Basin) are described in this section of the report. Hydrogeologic units of the Bear River Basin are identified on **Plate 5**. Most geologic descriptions were modified from Clarey (2011).

7.2 Cenozoic hydrogeologic units

Hydrogeologic units of Cenozoic (Quaternary and Tertiary) age are described in this section the report. Cenozoic hydrogeologic units are composed of both unconsolidated deposits such as sand and gravel (primarily of Quaternary age) and consolidated sediments (bedrock of Tertiary age) such as sandstone and conglomerate. Compared with aquifers of Mesozoic, Paleozoic, and Precambrian age, Cenozoic aquifers are the most used sources of water (Clarey, 2011). Cenozoic aquifers are used as a source of water for stock, domestic, industrial, irrigation, and public-supply purposes.

7.2.1 Quaternary unconsolidated-deposit aquifers

The physical and chemical characteristics of Quaternary unconsolidated deposits in the Bear River Basin are described in this section of the report.

Physical characteristics
Unconsolidated deposits of Quaternary age can contain aquifers (referred to herein as "Quaternary unconsolidated-deposit aquifers") that are highly productive locally, and are the source of water for many wells in the Bear River Basin. In the Bear River Basin, Quaternary unconsolidated-deposit aquifers are the most used sources of water, for stock, domestic, industrial, irrigation, and public-supply purposes.

Quaternary-age unconsolidated deposits are composed primarily of sand and gravel interbedded with finer-grained sediments such as silt and clay, although coarser deposits such as cobbles and boulders occur locally (Berry, 1955; Robinove and Berry, 1963; Rubey et al., 1980; Ahern et al., 1981; Glover, 1990; Eddy-Miller et al., 1996; Sunrise Engineering, 1997). Many different types of unconsolidated deposits of Quaternary age are present in the Bear River Basin (**Pl. 3**). Collectively, the unconsolidated deposits throughout the Bear River valley commonly are referred to as "valley fill" because the deposits grade into and (or) overlie one another and are bounded laterally or vertically (rest on top of) bedrock through which the Bear River and related tributaries have eroded to form the present-day valley (Robinove and Berry, 1963).

Quaternary-age alluvium is composed of unconsolidated, poorly to well sorted mixtures of clay, silt, sand, and gravel deposited along streams, primarily as channel-fill and flood-plain deposits. Locally, alluvium can include alluvial fan and terrace deposits, valley side colluvium or talus, and sediments deposited in small bogs, lakes, or deltas. Alluvium commonly grades laterally and vertically into other adjacent Quaternary (and in places, laterally into Tertiary) unconsolidated deposits; consequently, it is often difficult to determine where to differentiate the different types

of Quaternary unconsolidated deposits in the Bear River Basin. In addition, different investigators have not always been consistent when mapping/identifying ("lumping and splitting") the different types of Quaternary unconsolidated deposits. Furthermore, use of different scale geologic maps results in different groupings of the unconsolidated deposits.

Estimates of alluvium thickness vary substantially in the Bear River valley because few wells in the area fully penetrate the deposits. Robinove and Berry (1963) reported Quaternary-age alluvium thicknesses of 0 to 185 feet (ft) or more in the Bear River valley. Lines and Glass (1975, Sheet 1) reported that alluvium was at least 410-ft thick in the Bear River valley near the town of Border. The maximum thickness of alluvium along smaller stream valleys in the Bear River Basin such as the Smiths Fork generally is about 100 ft (Lines and Glass, 1975, Sheet 1). Glover (1990) reported that wells completed to a depth of 200 ft in the alluvium were common in the Cokeville area, and that well depths of 400 and 450 ft were known in the area. Alluvium commonly is locally thicker than 30 ft in the Kemmerer and Evanston areas (M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993).

Unconsolidated terrace deposits (also described as terrace gravel deposits or terrace, gravel, and fan deposits) are present throughout the Bear River Basin. Deposits generally are Quaternary in age, but some deposits are Tertiary (Pliocene) in age. Pliocene to Pleistocene (Tertiary and Quaternary) terrace deposits are composed of unconsolidated mixtures of silt, clay, sand, and coarse gravel located 30 to 100 ft or more above local streams; these deposits may be as much as 325-ft thick in western Wyoming and southeastern Idaho (Oriel and Platt, 1980). Robinove and Berry (1963, Table 1) reported thicknesses of as much as 50 ft or more for Quaternary terrace deposits in the Bear River valley. The Pleistocene to Holocene (Quaternary) terrace deposits consist of unconsolidated, poorly to moderately sorted, partly dissected, mixtures of silt, sand, and gravel. The deposits are as much as 15 to 250 ft above streams in the Cokeville area (Rubey et al., 1980). Pleistocene to Pliocene (?)

(Quaternary) older gravel deposits underlie the bench located east of the Smiths Fork River and are composed of unconsolidated and poorly sorted mixtures of pebble- to boulder-sized gravel, sand, silt, and clay; they may be as much as 150-ft thick in the Cokeville area (Rubey et al., 1980). The Sublette Flat area east of the town of Cokeville is underlain by areally extensive terrace deposits that are 200 ft or more in thickness (Lines and Glass, 1975). Areally extensive terrace deposits also are present in the Hilliard Flat area.

Colluvium is composed of unconsolidated and poorly sorted, angular debris mantling major stream valley sides, tributary stream valleys, and hill slopes. Locally, colluvium includes soil and gravel. Thickness varies, but colluvium commonly is 3 ft or more thick in the Kemmerer and Evanston areas (M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). Colluvium commonly is included (mapped) with other types of unconsolidated deposits such as alluvium (mapped as alluvium) on geologic maps of the area.

Quaternary alluvial fan deposits are common along the Bear River valley in the area located to the north of the town of Cokeville (WSGS Plate 1; Plate 3). The alluvial fan deposits are composed of unconsolidated, poorly sorted, alluvium and colluvium forming well defined fan-shaped deposits at mouths of tributary valleys. Berry (1955) indicated that the deposits were not as well sorted and were more angular than alluvium, indicating that the deposits were locally derived. Thickness varies but alluvial fan deposits commonly are 30 ft or more in thickness in the Kemmerer and Evanston areas (M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The upper parts of the alluvial fans generally are well drained of groundwater, and groundwater is not present except at deeper depths within the proximal and medial parts of the fan deposits and closer to local stream channels (Clarey, 2011). Berry (1955) stated that the deposits were not likely to yield as much water as alluvium.

Quaternary loess deposits, also defined as eolian deposits in some publications (for example, Robinove and Berry, 1963, Table 1), consist of

wind-blown, light brown, unconsolidated silt and fine-grained sand (Rubey et al., 1980; M'Gonigle and Dover, 1992). Robinove and Berry (1963, Table 1) reported thicknesses of as much as 10 ft or more in the Bear River valley, but deposits reportedly are as much as 150-ft thick in the Cokeville area (Rubey et al., 1980). The deposits locally form dunes about 10-ft thick in the Kemmerer area (M'Gonigle and Dover, 1992). The loess deposits commonly are mapped with other Quaternary unconsolidated deposits on geologic maps, including on **Plate 3.** In most of the Bear River Basin, these deposits are topographically high and drained of water (Robinove and Berry, 1963); however, they may "serve as catchment areas for precipitation" (Robinove and Berry, 1963, p. V21), and presumably provide recharge to underlying deposits. Where saturated, the deposits are likely to yield very small volumes of groundwater because of predominantly fine grain size (Robinove and Berry, 1963, Table 1).

Quaternary landslide deposits are composed of masses of older bedrock that have moved downward and are partly broken and disaggregated (Rubey et al., 1980). The landslide deposits are composed of slumps, landslides, and mudflows of soil, sediment, and rock debris, including unconsolidated, angular rock debris and large slump blocks that have moved downslope in mass under gravity. The deposits are 30 ft or more in thickness in the Kemmerer and Evanston areas (Dover and M'Gonigle, 1993). No wells completed in Quaternary landslide deposits in the Bear River Basin were located/inventoried as part of this study, but springs issue from the deposits in some areas (discharge for one spring listed on **Plate 4**). Robinove and Berry (1963, Table 1) speculated that Quaternary landslide deposits (identified as "slope wash, and rock debris") might be capable of yielding small quantities of water sufficient for domestic and stock use. Lines and Glass (1975, Sheet 1) noted that landslide deposits (identified as "rock debris") were not a potential source of water because of poor sediment sorting and small saturated thickness.

Quaternary (Pleistocene) glacial deposits consist of unconsolidated, unsorted to poorly sorted

mixtures of rock fragments (including boulders), silt, and clay. Deposits include tills and moraines of former mountain glaciers. Thickness varies but glacial deposits can be as much as 200-ft thick in the Cokeville area (Rubey et al., 1980). Moraine deposits may be 230 ft or more in thickness locally in the Evanston area (Dover and M'Gonigle, 1993); older moraine deposits in the same area may be 130 ft or more in thickness. Groundwater in the glacial deposits may be available for development where the unit is sufficiently water saturated, permeable, and in areas where a high content of sand and gravel is present in the deposits (Clarey, 2011).

Groundwater in Quaternary unconsolidated-deposit aquifers in the Bear River Basin typically is unconfined (water-table conditions predominate). Quaternary unconsolidated-deposit aquifers are small in areal extent and primarily occur in alluvium (commonly associated with colluvium and referred to herein as "alluvial aquifers") or terrace deposits (sometimes referred to as "terrace gravel deposits" or "terrace, gravel, and fan deposits" in some reports and referred to herein as "terrace-deposit aquifers") along valleys and in adjacent upland areas, and along streams and rivers in the Bear River Basin (**Pls. 3** and **5**). Consequently, most wells completed in Quaternary unconsolidated-deposit aquifers are located close to and along streams and rivers, primarily the Bear River. Along the flood plains, wells completed in alluvium are in hydraulic connection with streams and rivers, most notably along parts of the Bear River valley (Berry, 1955; Glover, 1990). Wells completed in the terrace deposits in the southern Bear River valley may "fail during relatively dry years because of the small saturated thickness" (Lines and Glass, 1975, Sheet 1). Although limited in the areal extent, Quaternary unconsolidated-deposit aquifers (primarily alluvial aquifers) are the most used aquifers in the Overthrust Belt, including the Bear River Basin (Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Ahern et al., 1981; Clarey, 2011).

Hydrogeologic data describing the Quaternary unconsolidated deposits in the Bear River Basin (alluvial aquifers, terrace-deposit aquifers, and

landslide deposits), including spring-discharge and well-yield measurements, and other hydraulic properties, are shown on **Plate 3** and summarized on **Plate 4**. Well yields in Quaternary alluvial and terrace-deposit aquifers in the Bear River Basin (**Pl. 4**) are directly related to the size and sorting of materials composing the deposits, as well as the saturated thickness of the deposits. In places, well yields are high because of large saturated thicknesses and very coarse deposits. Yields from wells completed in Quaternary alluvial aquifers ranged from 0.25 to 1,930 gallons per minute (gal/min), with a median of 20 gal/min (**Pl. 4**). Specific capacities for wells completed in Quaternary alluvial aquifers ranged from 0.3 to 150 gallons per minute per foot of drawdown [(gal/min)/ft] with a median of 18 (gal/min)/ft (**Pl. 4**). Estimates of transmissivity for wells completed in Quaternary alluvial aquifers ranged from 30.8 to 71,500 feet squared per day (ft²/day), with a median of 4,260 ft²/d (**Pl. 4**). One estimate of hydraulic conductivity for a well completed in a Quaternary alluvial aquifer was inventoried as part of this study and was 670 feet per day (ft/d) (**Pl. 4**). Of the remaining inventoried sites for Quaternary unconsolidated deposits, one well yield (14 gal/min) was inventoried for terrace-deposit aquifers, one well yield (20 gal/min) was inventoried for a spring issuing from terrace-deposit aquifers, and one discharge (2,000 gal/min) was inventoried for a spring issuing from landslide deposits (**Pl. 4**).

Hydraulic connection between the Bear River alluvial aquifer (stream-aquifer system composed of hydraulically connected Bear River and Quaternary-age alluvium) and underlying hydrogeologic units composed of bedrock in the Cokeville and Evanston areas (**Pls. 3** and **5**) was evaluated by Glover (1990). In the Cokeville area, the investigator determined that underlying aquifers in the Wasatch Formation, Nugget Sandstone, and Wells Formation (see **Pl. 6**) were not hydraulically connected to the Bear River alluvial aquifer. In contrast, the investigator determined that the Wasatch aquifer (composed of the Wasatch Formation) was in hydraulic connection with the Bear River alluvial aquifer in much of the Evanston area. Lower permeability rocks located on the upthrown sides of normal

faults locally have isolated the Wasatch aquifer from the Bear River alluvial aquifer in the Evanston area.

In parts of the eastern Bear River valley in Uinta County, groundwater-quality from some wells completed in the alluvium is reportedly "poor" (TriHydro Corporation, 2000, p. 2-2). The investigators (TriHydro Corporation, 2000, p. 2-2) speculated that the poor water quality is "most likely due to the close proximity of the deeper normal fault system along the eastern Bear River valley," and that "this deeper normal fault system may allow deeper groundwaters of higher mineral content and containing sulfides and/or sulfates to migrate upwards into the overlying Bear River alluvium" in the area. Similarly, Sunrise Engineering (1997) noted groundwater-quality problems from some wells completed in the Bear River alluvial aquifer in the city of Evanston. The investigators (Sunrise Engineering, 1997) noted that wells on the south side of the Bear River "have historically produced good quality water while wells on the north side of the river have historically been plagued by sulfur and other problems."

The areal extent of Quaternary unconsolidated-deposit aquifers coincides with most of the population and irrigated cropland in the Bear River Basin, making these aquifers particularly susceptible to contamination from anthropogenic activities. Areas where alluvial deposits are relatively thin (30 ft or less) and depth to groundwater is shallow (10 ft or less) are particularly susceptible to effects from overlying anthropogenic activities (Hamerlinck and Arneson, 1998). Evidence of groundwater contamination of Quaternary unconsolidated-deposit aquifers by anthropogenic activities in the Bear River Basin has been indicated by detection of elevated nitrate concentrations and by detection of pesticides (Eddy-Miller et al., 1996, Table 14; Eddy-Miller and Norris, 2000; Eddy-Miller and Remley, 2004).

Recharge, discharge, and groundwater movement

Recharge to Quaternary unconsolidated-deposit aquifers is not only from direct infiltration of precipitation (snow and rain) and ephemeral

and perennial streamflow losses, but also from infiltration of diverted surface water through unlined irrigation canals and ditches, from water applied to fields, and discharge from underlying bedrock aquifers (Berry, 1955; Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Ahern et al., 1981; Glover, 1990; Eddy-Miller et al., 1996; Sunrise Engineering, 1997). Some of the recharge to alluvium from streams may occur as water infiltrates the heads of alluvial fans along the margins of the Bear River valley (Lines and Glass, 1975, Sheet 1). In irrigated areas, water levels in the Quaternary unconsolidated-deposit aquifers in the Bear River Basin change in response to recharge from seasonal application of diverted surface water used to irrigate crops (Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Glover, 1990). Water levels are the highest (shallowest) during the growing season when irrigation water recharges the aquifers, and water levels are the lowest (deepest) after irrigation has ceased during the winter when water is discharged from the aquifers.

In the alluvial aquifer along the Bear River in the Cokeville area (referred to herein as the Bear River alluvial aquifer; areal extent shown on **Plate 6** as Quaternary alluvium and colluvium and Quaternary terrace, gravel, and fan deposits), water levels vary in response to changing seasonal recharge, primarily from irrigation diversions (for example, Glover, 1990, Figure 10). During the irrigation season, water levels in the aquifer typically begin to rise during the spring and early summer months after irrigation by diverted surface water begins, and gradually decrease during the late summer months after the quantity of diverted water begins to decrease and irrigation ceases. Water levels in the aquifer from October through March are relatively stable, and reflect steady-state or "near steady-state" conditions (Glover, 1990, p. 19).

Discharge from Quaternary unconsolidated-deposit aquifers occurs by evapotranspiration, gaining streams, seeps, drains, spring flows, and withdrawals from wells (Berry, 1955; Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Ahern et al., 1981; Glover, 1990; Eddy-Miller et al., 1996; Sunrise Engineering,

1997). Evapotranspiration from Quaternary unconsolidated-deposit aquifers is likely to be highest in the summer in areas where the water table in the Bear River Basin is at or near land surface (Robinove and Berry, 1963; Glover, 1990, p. 28).

The direction of horizontal groundwater flow in the Bear River alluvial aquifer, in the Cokeville area is shown on a steady-state potentiometric-surface map constructed by Glover (1990, Figure 9; reproduced herein as **Pl. 6**). Areas of Bear River streamflow loss to and gain from the alluvial aquifer also can be visually identified on the map; these losses and gains also were quantified by measuring streamflow at paired streamflow-gaging stations (using monthly mean discharge) during the months of November and December when diversions for irrigation were not in operation and sources of possible error were minimized (Glover, 1990, Table 1). Potentiometric contours in the immediate vicinity of streams can indicate gaining streams by pointing in an upstream direction (potentiometric surface above water in the stream) or losing streams by pointing in a downstream direction (potentiometric surface below water in the stream). The streamflow loss/gain study indicated the generally north-flowing Bear River gained about 36 cubic feet per second (ft³/s) from the alluvial aquifer in the study area (Glover, 1990, Table 1). Recharge to the alluvial aquifer from the Smiths Fork and associated tributaries, tributaries to the Bear River, is visually notable (**Pl. 6**), and the Smiths Fork lost about 19.4 ft³/s to the aquifer (Glover, 1990).

In other areas along the Bear River valley in the Bear River Basin, groundwater flow in the alluvial aquifers generally is towards the center of the river or stream valley or generally in a downstream direction paralleling the direction of the surface water flow in the river or streams, including as underflow parallel to streamflow (Berry, 1955; Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Ahern et al., 1981; Glover, 1990). In terrace-deposit aquifers, the direction of groundwater flow generally is toward the principal surface drainage.

Little information is available to evaluate the potential for vertical groundwater flow in Quaternary unconsolidated-deposit aquifers in the Bear River Basin; however, Glover (1990, p. 18) found two wells completed in the Bear River alluvial aquifer in the Cokeville area located closely together (about 30 ft) and completed at different depths (one well completed about 200-ft deep and the other completed about 400-ft deep). Static water levels were essentially the same, indicating that vertical gradients in the Bear River alluvial aquifer were small; however, it is unknown how representative this small vertical gradient is for unconsolidated-deposit aquifers at other locations in the Bear River Basin.

Cokeville area groundwater-flow model

Glover (1990) constructed a groundwater-flow model of the Bear River alluvial aquifer in the Cokeville area. In the study, the alluvial aquifer was defined as an unconfined aquifer composed of saturated Quaternary unconsolidated deposits (primarily alluvium, but included some hydraulically connected terrace deposits) along the Bear River and associated tributaries underlain by bedrock with much lower permeability. Areal extent of the Bear River alluvial aquifer model matches that of the potentiometric-surface map reproduced herein as **Plate 6** because the map was constructed as part of the same study.

The Bear River alluvial aquifer was simulated by Glover (1990) using the finite-element model of Glover (1988). The groundwater-flow model was constructed to improve estimates of aquifer properties and to evaluate the effects of pumpage from area wells completed in the Bear River alluvial aquifer, including large-capacity irrigation wells, on streamflow of the Bear River and associated tributaries. Hydrologic data collected as part of the study and from previous studies were used to construct and calibrate the model under steady-state conditions. Study emphasis was placed on understanding the effects of current and predicted groundwater withdrawals on streamflow.

A steady-state groundwater budget was constructed from collected data and from successful model simulations (Glover, 1990, Table 7). The simulated

water budget indicated that the Bear River gained about 36.8 ft³/s from the alluvial aquifer, and that the tributaries lost about 21.2 ft³/s to the alluvial aquifer through stream leakage. Underflow from the upstream model boundary was estimated at about 18.5 ft³/s, and underflow across the downstream model boundary was estimated to be about 17.8 ft³/s. Underflow through alluvium along small tributaries of the Bear River was estimated to be an additional 14.9 ft³/s.

Steady-state and transient simulations were used to refine aquifer property estimates and to determine the distribution of groundwater recharge. The 1980 and 1981 irrigation seasons were used for calibration of transient simulations. Although steady-state groundwater recharge was primarily from stream leakage and underflow, seasonal recharge during the irrigation season occurred primarily in areas with large amounts of irrigation by diverted surface water. Calculated groundwater budgets for the 1980 and 1981 irrigation seasons indicated that the main source of recharge to the aquifer during the irrigation season was from flood-irrigated fields, whereas the main discharge area was to the Bear River. The investigator also concluded that groundwater pumpage from the alluvial aquifer was small compared with other groundwater discharge components.

The effects of pumping on streamflow during years of average, greater-than-average, or less-than-average streamflow also were evaluated. The effects of pumping on streamflow during years of average and greater-than-average streamflow could not be simulated because groundwater withdrawal rates were very small, and the effects of pumping were less than the accuracy of streamflow measurements.

The effects of pumping on streamflow were simulated for a year of less-than-average flow (1977). For 1977, the simulation indicated that streamflow was reduced a maximum of about 3.4 ft³/s during August, within the period when maximum pumping typically occurs (July and August). The simulation indicated that by the start of the next irrigation season, the effects of pumping during the previous year would be reduced to less

than 0.5 ft³/s. Lastly, Glover (1990) estimated that about 84 percent of the water pumped by wells was derived from water that otherwise would have discharged to the Bear River, and 16 percent from water that otherwise would have been consumed by phreatophytes.

Evanston area streamflow depletion study
Glover (1990) also attempted to construct a finite-element groundwater flow model for the Bear River alluvial aquifer in the Evanston area. Available hydrogeologic data was insufficient for construction of a groundwater-flow model for the area. Consequently, the investigator used an analytical streamflow-depletion method (Jenkins, 1968a, 1968b) to evaluate the effects on streamflow of the Bear River in the Evanston area from pumpage of supply wells in Evanston that were completed in the Bear River alluvial aquifer and underlying Wasatch aquifer. Use of the analytical streamflow-depletion method indicated that the largest reduction in streamflow occurred during the pumping season, and that streamflow was affected after the pumpage was ended. Most of the reduction in streamflow was due to pumping from the Bear River alluvial aquifer, not the Wasatch aquifer. Use of the analytical streamflow-depletion method also indicated that pumping from the Wasatch aquifer was likely to affect streamflow only after several months.

Chemical characteristics
The chemical characteristics of groundwater from Quaternary alluvial aquifers, terrace-deposit aquifers, and landslide deposits in the Bear River Basin are evaluated in this section of the report.

7.2.1.1 Quaternary alluvial aquifers

The chemical composition of groundwater in Quaternary alluvial aquifers in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from as many as 39 wells. Summary statistics calculated for available constituents are listed in **Appendix E**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G**, **Diagram A**). TDS concentrations were variable and indicated that most waters were fresh (90 percent of

samples) and remaining waters were slightly saline (**Appendix E; Appendix G, Diagram A**). TDS concentrations ranged from 212 to 1,770 mg/L, with a median of 458 mg/L.

Concentrations of some properties and constituents in water from Quaternary alluvial aquifers in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of some constituents exceeded health-based standards: mercury (one of three samples exceeded the USEPA MCL), nitrate plus nitrite (one of 18 samples exceeded the MCL of 10 mg/L), and nitrate (one of 26 samples exceeded the MCL of 10 mg/L). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (11 of 29 samples exceeded the SMCL of 500 mg/L), iron (two of 14 samples exceeded the SMCL of 300 μg/L), sulfate (four of 29 samples exceeded the SMCL of 250 mg/L), manganese (one of 11 samples exceeded the SMCL of 50 μg/L), and chloride (two of 29 samples exceeded the SMCL of 250 mg/L).

Concentrations of some constituents exceeded State of Wyoming standards for agricultural use in the Bear River Basin. Constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (5 of 29 samples exceeded the WDEQ Class II standard of 200 mg/L), chloride (4 of 29 samples exceeded the WDEQ Class II standard of 100 mg/L), and iron (1 of 14 samples exceeded the WDEQ Class II standard of 5,000 μg/L). Mercury was the only constituent measured in water from an alluvial aquifer at a concentration that exceeded applicable State of Wyoming livestock water-quality standards (the one uncensored sample exceeded the WDEQ Class III standard of 0.05 μg/L).

7.2.1.2 Quaternary terrace-deposit aquifers

The chemical composition of groundwater in Quaternary terrace-deposit aquifers in the Bear River Basin was characterized and the quality

evaluated on the basis of environmental water samples from nine wells and one spring. Summary statistics calculated for available constituents are listed in **Appendix E**, and major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G**, **Diagram B**). TDS concentrations were variable and indicated that most waters were fresh (90 percent of samples) and remaining waters were slightly saline (**Appendix E**; **Appendix G**, **Diagram B**). TDS concentrations ranged from 297 to 1,030 mg/L, with a median of 476 mg/L. Concentrations of some properties and constituents in water from Quaternary terrace-deposit aquifers in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, but concentrations of nitrate exceeded health-based standards (USEPA MCLs and HALs): two of eight samples exceeded the MCL of 10 mg/L. Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (five of 10 samples exceeded the SMCL of 500 mg/L), manganese (one of two samples exceeded the SMCL of 50 µg/L), sulfate (one of 10 samples exceeded the SMCL of 250 mg/L), and pH (one of 10 samples above upper SMCL limit of 8.5).

Concentrations of some properties and constituents in water from Quaternary terrace-deposit aquifers exceeded State of Wyoming standards for agricultural and livestock use in the Bear River Basin. Constituents in environmental water samples that had concentrations greater than agricultural-use standards were chloride (two of 10 samples exceeded the WDEQ Class II standard of 100 mg/L) and sulfate (one of 10 samples exceeded the WDEQ Class II standard of 200 mg/L). One property (pH) had values outside the range for livestock-use standards (one of 10 samples above upper WDEQ Class III limit of 8.5).

7.2.1.3 Aquifers in Quaternary landslide deposits

The chemical composition of groundwater in Quaternary landslide deposits in the Bear River Basin was characterized and the quality

evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram C**). The TDS concentration (187 mg/L) indicates that the water from the spring was fresh.

On the basis of the properties and constituents analyzed, the quality of water from the spring was suitable for most uses. No properties or constituents in water were measured at concentrations that approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.2.2 Tertiary hydrogeologic units

Tertiary hydrogeologic units are described in this section of the report. Although composed of rocks of both Paleocene and Late Cretaceous age, the Evanston Formation is included with Tertiary hydrogeologic units for descriptive purposes. Most wells completed in Tertiary hydrogeologic units in the Bear River Basin are for stock or domestic use, but a few are for public-supply or irrigation use. Tertiary formations comprising the hydrogeologic units are composed of nonmarine (continental) mixtures of many different lithologies, including shale, mudstone, siltstone, sandstone, conglomerate, lacustrine limestone, and volcanic tuff. These Tertiary formations commonly intertongue or interfinger with other formations, are relatively flat-lying, and unconformably overlie eroded and older formations.

7.2.2.1 Salt Lake aquifer

The Pliocene and Miocene Salt Lake Formation comprises the Salt Lake aquifer in the Bear River Basin (**Pl. 5**). The Salt Lake Formation consists of pale reddish gray conglomerate, sandstone, siltstone, clay, and white volcanic ash (Rubey, 1973; Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey et al., 1980; Ahern et al., 1981, Table IV-1). Reported thickness of the Salt Lake Formation in the Overthrust Belt ranges from 0 to 1,000 ft (Lines and Glass, 1975, Sheet 1). The

Salt Lake Formation is present in some of the structurally down-dropped valley floors within the Overthrust Belt.

The Salt Lake Formation was classified as a major aquifer by Ahern et al. (1981) and in the Statewide Framework Water Plan (WWC Engineering et al., 2007), and that definition was tentatively retained herein (**Pl. 5**). Ahern et al. (1981, Table IV-1) reported a spring discharge of 8,000 gal/min for the Salt Lake aquifer in the Overthrust Belt. No data were located describing the physical and chemical characteristics of the hydrogeologic unit in the Bear River Basin as part of this study.

7.2.2.2 Bishop Conglomerate

The Oligocene Bishop Conglomerate occurs only in very limited areas in the southeastern part of the Bear River Basin (**Pl. 3**) as isolated caps believed to be remnants of a formerly more extensive depositional sheet that capped a pediment surface graded to the Uinta Mountains (Dover and M'Gonigle, 1993). The Bishop Conglomerate consists of well-rounded cobbles and boulders of quartzite, limestone, and metamorphic rocks (Bradley, 1964, p. 55; Lines and Glass, 1975, Sheet 1; Dover and M'Gonigle, 1993). Reported thickness of the Bishop Conglomerate ranges from 0 to 200 ft in the Overthrust Belt and adjacent areas (Lines and Glass, 1975, Sheet 1).

Little information is available for describing and assessing the hydrogeologic characteristics of the Bishop Conglomerate. No wells or springs associated with the Bishop Conglomerate in the Bear River Basin were inventoried as part of this study. In the Green River, Great Divide, and Washakie Basins to the east, Welder (1968, Sheet 2) and Welder and McGreevy (1966, Sheet 2) reported that the potential for groundwater development in the Bishop Conglomerate is not known, but is likely poor to fair. Welder (1968, Sheet 2) indicated that the deposits in the Green River Basin typically are topographically high and, consequently, probably well-drained in most areas. Bartos and Hallberg (2010) inventoried five measurements of spring discharge and one measurement of well yield for the Bishop

Conglomerate in the Green River Basin (located east of the Bear River Basin). The five reported spring discharges ranged from 5 to 200 gal/min with a median discharge of 15 gal/min. The one measurement of well yield was 42 gal/min.

7.2.2.3 Fowkes aquifer

The physical and chemical characteristics of the Fowkes aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics
The Fowkes aquifer is composed of the Eocene Fowkes Formation in the Bear River Basin (**Pl. 5**). The Fowkes Formation consists of a basal conglomerate overlain by tuffaceous mudstone, tuffaceous, calcareous sandstone, and rhyolitic ash. Thickness of the formation ranges from 0 to 2,600 ft (Oriel and Platt, 1980; Ahern et al., 1981, Table IV-1). The Fowkes Formation is divided into the Sillem, Bulldog Hollow, and Gooseberry Members (Oriel and Tracey, 1970; Lines and Glass, 1975) (individual members not shown on **Plate 5**). The Sillem Member is composed of a basal conglomerate overlain by mudstone and claystone interbedded with sandstone and algal limestone, and ranges from 100 to 400 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The Bulldog Hollow Member is composed primarily of green and white tuffaceous mudstone and green to buff and brown tuffaceous, calcareous sandstone, and ranges from 200 to 2,000 ft in thickness (Oriel and Tracey, 1970; Nelson, 1973; Lines and Glass, 1975, Sheet 1; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The Gooseberry Member is composed primarily of light gray to white conglomerate and calcareous rhyolitic ash, and is more than 200-ft thick (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992).

The Fowkes Formation is considered to be an aquifer in the Overthrust Belt by previous investigators (Robinove and Berry, 1963, Plate 1; Lines and Glass, 1975, Sheet 1; Ahern et al., 1981; TriHydro Corporation, 2002, 2003) (**Pl. 5**).

Robinove and Berry (1963, Plate 1) reported that the Fowkes Formation in the Bear River valley was capable of yielding small quantities of groundwater. Lines and Glass (1975, Sheet 1) noted that tuffaceous sandstones in the Fowkes Formation are probably capable of yielding small quantities of water to wells. Ahern et al. (1981, Figure II-7) classified the formation as a major aquifer in the Overthrust Belt (**Pl. 5**) and noted that both springs issuing from and wells completed in the formation locally yielded water. In the Wyoming Water Framework Plan, the Fowkes Formation was classified as a major sandstone aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**).

Hydrogeologic data describing the Fowkes aquifer in the Bear River Basin, including spring-discharge and well-yield measurements, and other hydraulic properties, are shown on **Plate 3** and summarized on **Plate 4**. Spring discharge for three inventoried measurements ranged from 2 to 125 gal/min with a median of 5 gal/min (**Pl. 4**). Four measurements of well yield were inventoried for the Fowkes aquifer, and well yields ranged from 100 to 530 gal/min, with a median of 184 gal/min. One measurement of specific capacity was inventoried and was 0.63 (gal/min)/ft.

TriHydro Corporation (2002) described a 403-ft deep irrigation well (identified as the Thompson #4 and located in the SE¼, NE¼, section 12, T24N, R119W of Lincoln County, Wyoming) completed in the Fowkes Formation. The well reportedly yields as much as 1,000 gal/min from the Gooseberry Member of the Fowkes Formation that underlies Quaternary terrace deposits of the Sublette Flat area. The investigators reported that some groundwater from the overlying Quaternary terrace deposits moves downward and provides recharge to the underlying Fowkes aquifer.

TriHydro Corporation (2003) described two wells (identified as PCC#1 or South Martin well and PCC#2 or North Martin well) completed in the Fowkes aquifer with reported total depths of 320 and 350 ft, respectively, located near the mouth of Fowkes Canyon (located in the SW¼, NE¼, section 32, T17N, R120W, Uinta County). The water-bearing zones were identified as being composed of sandstone and conglomeratic sandstone from 240 to 320 ft below land surface. Measured static water levels were about 20 to 21 ft below land surface. A short duration (6 hour) constant-rate discharge aquifer test was conducted by pumping the South Martin well and using the North Martin well as an observation well. Based on the aquifer test, the following physical properties of the Fowkes aquifer were estimated: transmissivity of about 147 ft^2/d [1,100 gallons per day per foot (gpd/ft)] using discharge data, and about 161 ft^2/d [1,200 gpd/ft] using recovery data; hydraulic conductivity of about 3.8 ft/d [28.2 gallons per day per square foot (gpd/ft^2)]; specific capacity of 0.63 (gal/min)/ft; and a storage coefficient of 0.00024 (all values are shown individually or included as part of summary ranges provided on **Plate 4**).

Chemical characteristics

The chemical composition of groundwater for the Fowkes aquifer was characterized and the quality evaluated on the basis of environmental water samples from five wells completed in and three springs issuing from the Fowkes aquifer in the Bear River Basin. Summary statistics calculated for available constituents are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G**, **Diagram D**). TDS concentrations were variable and indicated that most waters were fresh (83 percent of samples) and remaining waters were slightly saline (**Appendix E**; **Appendix G**, **Diagram D**). TDS concentrations ranged from 248 to 1,570 mg/L, with a median of 537 mg/L.

Concentrations of a few properties and constituents in water from the Fowkes aquifer in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one property and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (three of six samples exceeded the SMCL of 500 mg/L) and chloride (one of six samples exceeded the SMCL of 250 mg/L). Chloride was the only constituent measured at concentrations

that exceeded State of Wyoming agriculture water-quality standards: (3 of 6 samples exceeded the WDEQ Class II standard of 100 mg/L). No properties or constituents had measurements or concentrations that approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.2.2.4 Conglomerate of Sublette Range

The Eocene and Paleocene Conglomerate of Sublette Range (Love et al., 1993) (**Pl. 5**) primarily consists of white, pink, dark gray, well-rounded, poorly sorted, pebble to boulder gravel composed of quartzite and gray chert mixed with silt and sand. Age and stratigraphic relation to the Evanston and Wasatch Formations is uncertain (Love et al., 1993). The formation may be as much as 600-ft thick in the Cokeville area (Oriel and Platt, 1980; Rubey et al., 1980; Salat, 1989; Salat and Steidtmann, 1991). The Conglomerate of Sublette Range is exposed only in several small outcrop areas in the Sublette Range, northwest of the town of Cokeville (T25N–T26N, R118W–R119W, Lincoln County, Wyoming). No data were located describing the physical and chemical characteristics of the lithostratigraphic unit.

7.2.2.5 Green River aquifer and confining unit

The physical and chemical characteristics of the Green River aquifer and confining unit in the Bear River Basin are described in this section of the report.

Physical characteristics
The Green River aquifer and confining unit is composed of the Eocene Green River Formation in the Bear River Basin (**Pl. 5**). The Green River Formation in the Bear River Basin is divided into the Fossil Butte and Angelo Members (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993) (individual members not shown on **Plate 5**).

The Fossil Butte Member of the Green River

Formation consists of light gray, tan, and light tan limestone, calcareous siltstone, marlstone, and shale; brown, laminated carbonaceous shale; and very thinly laminated oil shale. Tuffaceous interbeds are common and some calcareous beds rich in fossil fish are present, in addition to algal, gastropodal, and ostracodal limestone beds, mainly along the margins of the basin between Sillem Ridge and the Absaroka thrust fault. The Fossil Butte Member of the Green River Formation grades into and interfingers with the light gray to light tan sandstone and light red mudstone beds of the Wasatch Formation to the south and southwest. Thickness of the Fossil Butte Member ranges from 200 to 325 ft (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993).

The Angelo Member of the Green River Formation consists of light gray to light tan, white-weathering, siliceous limestone, calcareous shale, and siltstone. The unit also includes minor interbedded tan laminated limestone, brown algal limestone, marlstone, sandstone, and brown organic shale. Calcareous beds in the Angelo Member of the Green River Formation interfinger with sandstone and shale beds of the Wasatch Formation to the south and southwest. Thickness of the Angelo Member ranges from 0 to 200 ft (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993).

Little information is available describing the hydrogeologic characteristics of the Green River Formation in the Overthrust Belt, including the Bear River Basin. However, extensive study of the Green River Formation in the adjacent Green River Basin provides some insight into hydrogeologic properties of the unit. Hydrogeologic characteristics of the Green River Formation in the Green River Basin vary substantially, primarily because of changes in lithology. Consequently, the Green River Formation is classified as an aquifer, confining unit, or both, depending upon lithologic characteristics in the area of the Green River Basin examined (Ahern et al., 1981; Martin, 1996; Naftz, 1996; Glover et al., 1998; Bartos and Hallberg,

2010). Because similar differences in Green River Formation lithology also occur in the Bear River Basin, the lithostratigraphic unit is classified as an aquifer and confining unit herein (**Pl. 5**).

Few hydrogeologic data were available describing the Green River aquifer and confining unit in the Bear River Basin. One measurement of discharge from a spring issuing from the Angelo Member of the Green River was inventoried and was 1 gal/min (**Pl. 4**). Seven measurements of discharge for springs issuing from the Fossil Butte Member of the Green River Formation were inventoried and ranged from 5 to 200 gal/min, with a median of 14 gal/min.

Chemical characteristics

The chemical composition of groundwater in the Green River aquifer and confining unit in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from eight springs—one spring issuing from the Angelo Member and seven springs issuing from the Fossil Butte Member. Summary statistics calculated for available constituents are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on trilinear diagrams (**Appendix G**, **Diagram E** and **Diagram F** for the Angelo and Fossil Butte Members, respectively). TDS concentrations indicated that waters were fresh (**Appendix E**; **Appendix G, Diagram E** and **Diagram F**). The TDS concentration in the Angelo Member was 244 mg/L. TDS concentrations in the Fossil Butte Member ranged from 333 to 908 mg/L, with a median of 751 mg/L.

Concentrations of few properties and constituents in water from the Green River aquifer and confining unit in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. On the basis of the few properties and constituents analyzed for in the Angelo Member spring sample, waters were likely suitable for most uses as no properties or constituents approached or

exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards. Concentrations of one property and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use of the Fossil Butte Member: TDS (five of six samples exceeded the SMCL of 500 mg/L) and sulfate (five of six samples exceeded the SMCL of 250 mg/L). Concentrations of one constituent exceeded State of Wyoming agriculture water-quality standards: sulfate (five of six samples exceeded the WDEQ Class II standard of 200 mg/L). No properties or constituents had concentrations that approached or exceeded applicable State of Wyoming livestock water-quality standards in samples from the Fossil Butte Member.

7.2.2.6 Wasatch aquifer

The physical and chemical characteristics of the Wasatch aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics

The Eocene Wasatch Formation comprises the Wasatch aquifer in the Bear River Basin (**Pl. 5**). Currently (2013) used as a source of water for domestic, stock, industrial, and public-supply purposes, the Wasatch aquifer is the second most utilized aquifer in the Bear River Basin, although withdrawals are much smaller than withdrawals from the Quaternary unconsolidated-deposit aquifers.

The Wasatch Formation consists of variegated mudstone, claystone, siltstone, shale, sandstone, conglomeratic sandstone, and conglomerate. It is a thick sequence of nonmarine sedimentary rock with named members of the formation (discussed below but individual members not shown on **Plate 5**) in some areas. The Wasatch Formation and various members interfinger eastward with the members of the Green River Formation in the Fossil Basin and Green River Basin.

The Wasatch Formation in the Bear River Basin is divided into a basal conglomerate, a lower unnamed member, the main body of the formation, and the Bullpen and Tunp Members

(Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The basal conglomerate is a lenticular conglomerate of sandstone pebbles and cobbles, and ranges from 0 to 300 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992). The lower unnamed member is composed predominantly of drab-colored mudstone and sandstone, and ranges from 0 to 300 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992). The main body is composed predominantly of red, purple, and tan mudstone, with some sandstone, and ranges from 1,500 to 2,000 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The Bullpen Member is composed predominantly of red and salmon colored mudstone, and gray and brown mudstone, and ranges from 0 to 400 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; M'Gonigle and Dover, 1992). The Tunp Member is composed of conglomeratic mudstone and diamictite, and ranges from 200 to 500 ft in thickness (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; Hurst, 1984; Hurst and Steidtmann, 1986; M'Gonigle and Dover, 1992). Parts of the Wasatch Formation are composed of diamictite, especially the Tunp Member.

The Wasatch Formation is considered to be an aquifer in the Overthrust Belt by previous investigators (Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Ahern et al., 1981; Forsgren Associates, Inc., 2000; TriHydro Corporation, 2000, 2003) (**Pl. 5**). In the Wyoming Water Framework Plan, the Wasatch Formation is classified as a major aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**). The Wasatch aquifer is an important aquifer in the adjacent Green River Basin to the east (Ahern et al., 1981; Martin, 1996; Naftz, 1996; Glover et al., 1998; Bartos and Hallberg, 2010). Ahern et al. (1981, Figure II-7) classified the formation as a major aquifer in the Overthrust Belt (**Pl. 5**) and noted that both springs issuing from and wells completed in the formation

locally yielded water. The Wasatch Formation has been defined as a "productive aquifer" in the Deer Mountain Subdivision area near the town of Bear River in the Bear River Basin (Forsgren Associates, Inc., 2000, p. 3-2; TriHydro Corporation, 2000, p. 3-2).

Although little information was available at the time of their studies, Berry (1955) and Robinove and Berry (1963) speculated that small to moderate yields sufficient for domestic and stock use were likely from permeable beds in the Wasatch Formation. Lines and Glass (1975, Sheet 1) noted that conglomeratic sandstones and conglomerates in the Wasatch Formation likely were capable of yielding "moderate to large quantities" of water to wells. In addition, the investigators (Lines and Glass, 1975, Sheet 1) noted that fine-grained sandstones in the Wasatch Formation were capable of yielding "small to moderate" quantities of water, but that well yields were likely "greatly dependent" on saturated sandstone bed thickness. Similarly, Ahern et al. (1981) noted that permeable sandstones, conglomeratic sandstones, and conglomerates of the Wasatch Formation could yield moderate to large quantities of water to wells. Sandstones, conglomeratic sandstones, and conglomerates composing the Wasatch aquifer primarily are under confined conditions, except in outcrop areas where unconfined (water-table) conditions are present.

Hydrogeologic data describing the Wasatch aquifer in the Bear River Basin, including spring-discharge and well-yield measurements, and other hydraulic properties, are shown on **Plate 3** and summarized on **Plate 4**. Measured discharges of springs issuing from the Wasatch aquifer ranged from 0.5 to 75 gal/min with a median of 5 gal/min (**Pl. 4**).Yields from wells completed in the Wasatch aquifer ranged from 0.1 to 1,300 gal/min, with a median of 27.5 gal/min (**Pl. 4**). Specific capacities for wells completed in the Wasatch aquifer ranged from 0.2 to 14 (gal/min)/ft with a median of 0.7 (gal/min)/ft (**Pl. 4**). Estimates of transmissivity for wells completed in the Wasatch aquifer ranged from 26.8 to 4,020 ft²/d, with a median of 92.3 ft²/d (**Pl. 4**). One estimate of hydraulic conductivity for a well completed in the Wasatch was inventoried

and was 4.3 ft/d (**Pl. 4**).

Additional insight into Wasatch aquifer hydraulic characteristics in the Bear River Basin is provided by one recent study with a well-documented aquifer test (TriHydro Corporation, 2003). One well in the Deer Mountain area near the town of Bear River (Deer Mountain #6 Well, located in the SE¼, SW¼, section 2, T16N, R121W, Uinta County) was completed to a depth of about 544 ft below land surface in the Wasatch aquifer. Two primary water-bearing zones consisting of sandstone and conglomeratic sandstone were screened from about 272 to 313 ft below land surface and from about 502 to 523 ft below land surface. The static water level was measured at about 47 ft below land surface. Three step-drawdown discharge tests were conducted by pumping the Deer Mountain #6 well at rates of 75, 100, and 125 gal/min to help determine an optimal pumping rate for a constant-rate discharge aquifer test. Subsequently, a 5-day, single-well, constant-rate discharge aquifer test was conducted by pumping the Deer Mountain #6 well at a rate of 100 gal/min. Based on the aquifer test, the following physical properties of the Wasatch aquifer were estimated: transmissivity was estimated to be about 97 ft^2/d [727 gpd/ft] and 112 ft^2/d [836 gpd/ft] using drawdown data and about 87 ft^2/d [650 gpd/ft] and 118 ft^2/d [884 gpd/ft] using recovery data; hydraulic conductivity of about 4.3 ft/d [32 gpd/ft^2]; and a specific capacity of 0.71 (gal/min)/ft (all values shown individually or included as part of summary ranges provided on **Plate 4**).

The Wasatch aquifer likely receives substantial recharge where overlain by Quaternary-age alluvium in the Bear River valley (Glover, 1990; Forsgren Associates, Inc., 2000). Hydraulic connection between the Bear River alluvial aquifer (stream-aquifer system composed of hydraulically connected Bear River and Quaternary-age alluvium) and the underlying Wasatch aquifer, in the Cokeville and Evanston areas (**Pls. 3** and **5**) was evaluated by Glover (1990). In the Cokeville area, the investigator determined that the Wasatch aquifer was not hydraulically connected to the Bear River alluvial aquifer. In contrast, the investigator determined that the Wasatch aquifer was in hydraulic connection with the Bear River alluvial aquifer in much of the Evanston area. Lower permeability rocks located on the upthrown sides of normal faults have isolated the Wasatch aquifer from the Bear River alluvial aquifer in some of the Evanston area.

Glover (1990) used an analytical streamflow-depletion method (Jenkins, 1968a, 1968b) to evaluate the effects on streamflow of the Bear River in the Evanston area from pumpage of supply wells in Evanston that were completed in the Bear River alluvial aquifer and underlying Wasatch aquifer. Use of the analytical streamflow-depletion method indicated that the largest reduction in streamflow occurred during the pumping season, and that streamflow was affected after the pumpage was ended. Most of the reduction in streamflow was due to pumping from the Bear River alluvial aquifer, not the Wasatch aquifer. Use of the analytical streamflow-depletion method also indicated that pumping from the Wasatch aquifer was likely to affect streamflow only after several months.

Chemical characteristics

The chemical composition of groundwater in the Wasatch aquifer in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from 15 wells and nine springs. Summary statistics calculated for available constituents are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram G**). TDS concentrations were variable and indicated that most of the waters were fresh (90 percent of samples) and remaining waters were slightly to moderately saline (**Appendix E; Appendix G, Diagram G**). TDS concentrations ranged from 176 to 5,400 mg/L, with a median of 411 mg/L.

Concentrations of some properties and constituents in water from the Wasatch aquifer in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic

use, but concentrations of some constituents exceeded health-based standards (USEPA MCLs and HALs): radon (in the one sample analyzed for this constituent, the concentration exceeded the proposed USEPA MCL of 300 pCi/L, but did not exceed the alternative MCL of 4,000 pCi/L) and arsenic (one of seven samples exceeded the MCL of 10 µg/L). Concentrations of several properties and constituents exceeded aesthetic standards for domestic use: aluminum (the one uncensored sample of 100 µg/L exceeded the USEPA lower SMCL limit of 50 µg/L), iron (five of 13 samples exceeded the SMCL of 300 µg/L), TDS (seven of 20 samples exceeded the SMCL of 500 mg/L), manganese (two of nine samples exceeded the SMCL of 50 µg/L), sulfate (three of 21 samples exceeded the SMCL of 250 mg/L), chloride (two of 21 samples exceeded the SMCL of 250 mg/L), and pH (one of 22 samples above upper SMCL limit of 8.5).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the Bear River Basin. Properties and constituents in environmental water samples measured at concentrations greater than agricultural-use standards were SAR (two of 12 samples exceeded the WDEQ Class II standard of 8), sulfate (three of 21 samples exceeded the WDEQ Class II standard of 200 mg/L), chloride (four of 21 samples exceeded the WDEQ Class II standard of 100 mg/L), and TDS (one of 20 samples exceeded the WDEQ Class II standard of 2,000 mg/L). Properties and constituents measured at concentrations greater than livestock-use standards were chloride (one of 21 samples exceeded the WDEQ Class III standard of 2,000 mg/L), TDS (one of 20 samples exceeded the WDEQ Class III standard of 5,000 mg/L), and pH (one of 22 samples above upper WDEQ Class III limit of 8.5).

7.2.2.7 Evanston aquifer

The physical and chemical characteristics of the Evanston aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics
The Evanston aquifer is composed of the Paleocene and Upper Cretaceous Evanston Formation in the Bear River Basin (**Pl. 5**). The Evanston Formation consists of interbedded gray siltstone, sparse red sandstone, and minor lignite/coal beds; thickness is about 820 ft (Oriel and Platt, 1980). The Evanston Formation has been divided into an unnamed lower member, the Hams Fork Conglomerate Member, and a main body (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993) (individual members not shown on **Plate 5**).

The unnamed lower member of the Evanston Formation consists of gray, brown, and black shale; gray, green, yellow, and brown siltstone; thin- to massively-bedded, fine- to coarse-grained sandstone; and thin coal beds. Locally, the unnamed lower member contains gray quartzite and brown and black chert-pebble conglomerate at the base of the member (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993).

The Hams Fork Conglomerate Member of the Evanston Formation consists of pebble to boulder conglomerate containing well-rounded, pebble, cobble and boulder gravel of quartzite, chert, and limestone; gray and brown sandstone; and gray mudstone. The unit is about 1,000-ft thick in the Bear River Basin (Oriel and Tracey, 1970; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993).

The main body of the Evanston Formation is as much as 650-ft thick and consists of gray, carbonaceous claystone and siltstone with interbedded tan sandstone. Coal interbeds are present locally (Oriel and Tracey, 1970, Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993).

Previous investigators classified the Evanston

Formation as an aquifer. Robinove and Berry (1963, Plate 1) speculated that the Evanston Formation in the Bear River valley "may be capable of yielding small supplies of groundwater." Lines and Glass (1975, Sheet 1) noted that conglomeratic sandstones and conglomerates in the Evanston Formation likely were capable of yielding "moderate to large quantities" of water to wells, and that fine-grained sandstones were capable of yielding "small to moderate" quantities of water, but that well yields were likely "greatly dependent" on saturated sandstone bed thickness. Ahern et al. (1981, Table IV-1) classified the Evanston Formation in the Overthrust Belt as a minor aquifer, and that definition was retained herein (**Pl. 5**). The investigators noted that conglomerates and conglomeratic sandstones present in the unit were capable of yielding "moderate to large quantities of water to wells" (Ahern et al., 1981, Table IV-1, p. 46).

Areas of the Evanston Formation with fine-grained lithologies can act as confining units. Glover (1990, p. 52) noted that fine-grained impermeable lithologies of the upper Evanston Formation in the area immediately south of the Medicine Butte Fault provided hydraulic isolation between the Bear River alluvial aquifer and underlying bedrock aquifers.

Hydrogeologic data describing the Evanston aquifer in the Bear River Basin, including spring-discharge and well-yield measurements, and specific capacity, are shown on **Plate 3** and summarized on **Plate 4**. One spring discharge of 25 gal/min was inventoried (**Pl. 4**). Two measurements of well yield (0.5 and 200 gal/min) were inventoried for the Evanston aquifer (**Pl. 4**). One measurement of specific capacity was inventoried and was 20 (gal/min)/ft.

Chemical characteristics
The chemical composition of groundwater in the Evanston aquifer in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on

a trilinear diagram (**Appendix G, Diagram H**). The TDS concentration from the spring (662 mg/L) indicated that the water was fresh, and the TDS concentration from the well (4,880 mg/L) indicated that the water was moderately saline (**Appendix E; Appendix G, Diagram H**).

The chemical composition of groundwater in the Evanston aquifer also was characterized and the quality evaluated on the basis of one produced-water sample from one well completed in the Evanston aquifer. Summary statistics calculated for available constituents are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram A**). The TDS concentration from the well (4,400 mg/L) indicated that the waters were moderately saline (**Appendix F; Appendix H, Diagram A**).

Concentrations of some properties and constituents in environmental water samples from the Evanston aquifer in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards (USEPA MCLs and HALs). Concentrations of several properties and constituents frequently exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (well and spring samples exceeded the SMCL of 500 mg/L), chloride (well sample exceeded the SMCL of 250 mg/L), iron (well sample exceeded the SMCL of 300 μg/L), fluoride (well sample exceeded the SMCL of 2 mg/L), manganese (well sample exceeded the SMCL of 50 μg/L), and sulfate (well sample exceeded the SMCL of 250 mg/L).

Chemical analyses of many properties and constituents were not available for the produced-water samples; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water sample had concentrations of one property and one constituent that exceeded aesthetic standards for domestic use:

TDS and chloride (USEPA SMCLs of 500 mg/L and 250 mg/L, respectively).

Concentrations of some properties and constituents in water from the Evanston aquifer exceeded State of Wyoming standards for agricultural and livestock use in the Bear River Basin. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (well and spring samples exceeded the WDEQ Class II standard of 200 mg/L), SAR (well sample exceeded the WDEQ Class II standard of eight), TDS (well sample exceeded the WDEQ Class II standard of 2,000 mg/L), and chloride (well sample exceeded the WDEQ Class II standard of 100 mg/L). No properties or constituents had concentrations that approached or exceeded applicable State of Wyoming livestock water-quality standards.

The produced-water sample had concentrations of one property and one constituent that exceeded agricultural-use standards: TDS and chloride (WDEQ Class II standards of 2,000 mg/L and 100 mg/L, respectively). Chloride was measured in the produced-water sample at a concentration that exceeded the WDEQ Class III livestock-use standard (2,000 mg/L).

7.3 Mesozoic Hydrogeologic Units

In the Bear River Basin, Mesozoic hydrogeologic units generally are composed of impermeable fine-grained rocks (for example, shale) that isolate discrete water-bearing units such as sandstone. Rocks composing the hydrogeologic sequence range from Lower Triassic to Upper Cretaceous (**Pl. 5**). The complex intertonguing and interfingering relation between the different facies within some of the hydrogeologic units creates numerous small permeable zones that can function as individual aquifers (or subaquifers). In addition, many of the lithostratigraphic units within this sequence consist of more than one sequence/facies, some of which function as confining units (shales and siltstones) and some as aquifers (sandstones and carbonates) (**Pl. 5**). Compared with aquifers of Cenozoic, Paleozoic, and Precambrian age, Mesozoic aquifers are the second most used source of water (Clarey,

2011).

Numerous petroleum (oil and gas) wells are completed in many of the formations composing the Mesozoic hydrogeologic units, but relatively few water wells are completed in the units. Most water wells completed in Mesozoic Hydrogeologic units are in outcrop areas where drilling depths are relatively shallow and waters are relatively fresh. Most of these wells are completed for domestic or stock purposes, but some have other uses, such as public supply. Much of the geologic and hydrogeologic data for the Mesozoic hydrogeologic units are from petroleum exploration. Groundwater in many of the hydrogeologic units, especially away from outcrop areas and at great depths, is highly mineralized and not suitable for most uses, as indicated by produced-water samples.

7.3.1 Adaville aquifer

The Upper Cretaceous Adaville Formation comprises the Adaville aquifer (**Pl. 5**) and consists of brown-weathering, gray sandstone, siltstone, and carbonaceous shale. The formation is as much as 2,100-ft thick and is conglomeratic in the upper part with coal beds present in the lower part (Oriel, 1969; Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey et al., 1980; Ahern et al., 1981; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The Lazeart Sandstone Member forms thick cliffs in outcrop and is composed of very light gray, yellow-brown, tan, fine- to medium-grained, lithic "salt and pepper" sandstone with interbedded brown-gray shale; coal is present in slopes between sandstone cliffs in outcrop (M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993).

The Adaville Formation was speculatively identified as either a "major aquifer" or "minor aquifer" in the Overthrust Belt by Ahern et al. (1981, Figure II-7, and Table IV-1); the classification of the lithostratigraphic unit as an aquifer was tentatively retained herein (**Pl. 5**). Lines and Glass (1975, Sheet 1) speculated that "small quantities" of water were likely available from the Lazeart Sandstone Member of the Adaville Formation in the Overthrust Belt. One well yield of 20 gal/min was

inventoried as part of this study (**Pl. 4**). No data were located describing the chemical characteristics of the hydrogeologic unit.

7.3.2 Hilliard confining unit

The Hilliard confining unit is composed of the Upper Cretaceous Hilliard Shale (**Pl. 5**). The Hilliard Shale consists of interbedded dark gray to tan claystone, siltstone, and sandy shale and ranges from 5,600- to 5,900-ft thick; sandstone also is present and sandstone content increases northward and westward (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey et al., 1980; Ahern et al., 1981; M'Gonigle and Dover, 1992; and Dover and M'Gonigle, 1993). The Hilliard Shale underlies the Adaville Formation and overlies the Frontier Formation in the southern Overthrust Belt (Pl. 5) and western Green River structural basin. The Hilliard Shale is not exposed above and to the west of the Absaroka thrust fault in the Kemmerer area where the Upper Cretaceous lower member of the Evanston Formation unconformably overlies the Lower Cretaceous Sage Junction Formation (M'Gonigle and Dover, 1992). East of the Overthrust Belt and the western Green River structural basin, the Hilliard Shale is the stratigraphic equivalent to the Baxter Shale, Steele Shale, and Niobrara Formation in Sweetwater and Carbon Counties.

Because of the predominance of fine-grained lithologies such as shale, the Hilliard Shale was classified as a major confining unit [aquitard] by previous investigators (Ahern et al., 1981, Figure II-7, and Table IV-1) and in the Wyoming Water Framework Plan (WWC Engineering et al., 2007, Figure 4-9), and that classification is retained herein (**Pl. 5**). Despite being classified as a confining unit, water likely can be obtained locally from the Hilliard confining unit in areas where discontinuous sandstone beds or zones with fractures are present (Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Ahern et al., 1981, Table IV-1). No data were located describing the physical and chemical characteristics of the hydrogeologic unit.

7.3.3 Frontier aquifer

The physical and chemical characteristics of the Frontier aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics
The Frontier aquifer is composed of the Upper Cretaceous Frontier Formation (**Pl. 5**). The Frontier Formation consists of interbedded white to brown fine- to medium-grained sandstone and dark gray shale with beds of abundant oyster fossils in the upper part of the formation (Oyster Ridge Sandstone Member), and coal and lignite beds in the lower part. Thickness of the Frontier Formation ranges from 2,200 to 3,000 ft (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey et al., 1980; Ahern et al., 1981; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The Frontier Formation is not exposed above and to the west of the Absaroka thrust fault (M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993), where the Upper Cretaceous lower member of the Evanston Formation unconformably overlies the Lower Cretaceous Sage Junction Formation. The Frontier Formation was divided into additional members by Hale (1960), including the Dry Hollow, Allen Hollow Shale, Coalville, and Chalk Creek Members. Individual members not shown on **Plate 5**.

Previous investigators have classified the Frontier Formation as an aquifer, and that definition is retained herein (**Pl. 5**). Robinove and Berry (1963, Plate 1) speculated that the Frontier Formation in the Bear River valley was "possibly an aquifer in areas." Lines and Glass (1975, Sheet 1) noted that sandstone aquifers in the Frontier Formation were capable of yielding moderate quantities of water and were the "best aquifers" in their "hydrogeologic division 5" (identified as being composed of Cretaceous shales and sandstones and shown on **Plate 5**) in the Overthrust Belt. Similarly, the Frontier Formation was classified as a minor aquifer yielding moderate quantities of water by Ahern et al. (1981, Figure II-7, and Table IV-1) in the Overthrust Belt and adjacent Green River Basin (**Pl. 5**). Interbedded discontinuous

sandstone beds compose the aquifer (Ahern et al., 1981; Lines and Glass, 1975, Sheet 1). Because sandstone beds compose the aquifer, permeability is primarily intergranular and related to the amount of cementation, except where fractured (Ahern et al., 1981). In the Wyoming Water Framework Plan, the Frontier Formation was classified as a minor aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**).

Hydrogeologic data describing the Frontier aquifer, including transmissivity, porosity, and permeability are shown on **Plate 3** and summarized on **Plate 4**. One estimate of transmissivity for one well completed in the Frontier aquifer was inventoried and was 2.68 ft²/d (**Pl. 4**). One porosity estimate obtained from petroleum exploration was available and was 16 percent (**Pl. 4**). One permeability estimate obtained from petroleum exploration was inventoried and was 30 millidarcy (**Pl. 4**).

Chemical characteristics
The chemical composition of groundwater in the Frontier aquifer in the Bear River Basin was characterized and the quality evaluated on the basis of one environmental water sample from a well. Individual constituent concentrations are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram II**). The TDS concentration (608 mg/L) indicated that the water was fresh (**Appendix E; Appendix G, Diagram II**).

The chemical composition of groundwater also was characterized and the quality evaluated on the basis of one produced-water sample from a well completed in the Frontier aquifer. Individual constituent concentrations are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram B**). The TDS concentration (11,600 mg/L) from the produced waters indicated that the water was very saline (**Appendix F; Appendix H, Diagram B**).

Concentrations of some properties and constituents in the Frontier aquifer in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality

standards and could limit suitability for some uses. On the basis of comparison of concentrations in one environmental water sample with health-based standards (USEPA MCLs and HALs), the environmental water was suitable for domestic use, but concentrations of one constituent exceeded health-based standards: gross-alpha radioactivity (USEPA MCL of 15 pCi/L). One property (TDS; USEPA SMCL of 500 mg/L) and one constituent (sulfate; SMCL of 250 mg/L) exceeded aesthetic standards for domestic use. Concentrations of some properties and constituents exceeded State of Wyoming standards for agriculture and livestock use in the Bear River Basin. Gross-alpha radioactivity and sulfate were measured in the environmental water sample at a concentration greater than their respective agricultural-use standards (WDEQ Class II standards of 15 pCi/L, and 200 mg/L, respectively). Gross-alpha radioactivity had a concentration that exceeded the State of Wyoming livestock standard (WDEQ Class III standard of 15 pCi/L).

Chemical analyses for few properties and constituents were available for the one produced-water sample; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. Nonetheless, concentrations of some properties and constituents in the Frontier aquifer in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. None of the constituents analyzed had applicable health-based standards; however, concentrations of TDS, chloride, and sulfate exceeded aesthetic standards (USEPA SMCLs of 500 mg/L, 250 mg/L, and 250 mg/L, respectively) for domestic use and exceeded State of Wyoming agricultural-use standards (WDEQ Class II standards of 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively). TDS and chloride concentrations exceeded livestock-use standards (WDEQ Class III standards of 5,000 mg/L and 2,000 mg/L mg/L, respectively). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in the produced-water sample.

7.3.4 Sage Junction Formation

The physical and chemical characteristics of the Sage Junction Formation in the Bear River Basin are described in this section of the report.

Physical characteristics
The Upper Cretaceous Sage Junction Formation (**Pl. 5**) is more than 3,000-ft thick and consists primarily of gray and tan siltstone, sandstone, and quartzite with minor amounts of porcellanite, limestone, conglomerate, and some coal beds (Rubey, 1973; Lines and Glass, 1975, Sheet 1; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The formation is a lateral western stratigraphic equivalent to part of the Aspen Shale. The uppermost several hundred feet of the Sage Junction Formation may be equivalent in age to the lower part of the Upper Cretaceous Frontier Formation (Rubey, 1973). The Sage Junction Formation is at least 3,375-ft thick above and to the west of the Absaroka thrust fault and in the northwestern part of the Kemmerer area (M'Gonigle and Dover, 1992). West and above the Absaroka thrust fault, the Upper Cretaceous lower member of the Evanston Formation unconformably overlies the Sage Junction Formation (M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993).

Changes in stratigraphic nomenclature between the western and eastern Cretaceous lithostratigraphic units occur at the Absaroka thrust fault in the Wyoming Overthrust Belt (Rubey, 1973). Lithostratigraphic units located above and to the west of the Absaroka thrust, including the hanging wall of the fault, are the western units (Smiths, Thomas Fork, Cokeville, Quealy, and Sage Junction Formations), whereas those located below and to the east of the Absaroka thrust, including the footwall of the fault, are the eastern units (Bear River Formation and Aspen Shale).

Few hydrogeologic data were available for the Sage Junction Formation. One measurement of discharge (0.2 gal/min) for a spring issuing from the Sage Junction Formation, and one measurement of well yield (15 gal/min) were inventoried as part of this study (**Pl. 4**).

Chemical characteristics
The chemical composition of groundwater in the Sage Junction Formation in the Bear River Basin was characterized and the quality evaluated on the basis of one environmental water sample from one spring. Individual constituent concentrations in the environmental water sample are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram J**). The TDS concentration (458 mg/L) indicated that the water was fresh. On the basis of the few properties and constituents analyzed for in the environmental water sample, the quality of water from Sage Junction Formation in the Bear River Basin was likely suitable for most uses. No concentrations of properties or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.3.5 Aspen confining unit

The physical and chemical characteristics of the Aspen confining unit in the Bear River Basin are described in this section of the report.

Physical characteristics
The Aspen confining unit is composed of the Upper and Lower Cretaceous Aspen Shale (**Pl. 5**). The Aspen Shale consists of interbedded light to dark gray shale, siltstone, and claystone with minor quartz-rich sandstone and porcellanite. Thickness of the Aspen Shale ranges from 800 to 2,000 ft (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The Aspen Shale is laterally equivalent to the Mowry Shale to the east. Some beds are present that are transitional from the Aspen Shale to the lower part of the Blind Bull Formation located north of the Bear River Basin (Rubey et al., 1980).

Little hydrogeologic information is available for the Aspen Shale in the Bear River Basin. The Aspen Shale was identified as either "discontinuous aquifers with local confining beds" or a "locally utilized aquifer" in the Overthrust Belt by Ahern et al. (1981, Figure II-7, and Table IV-1) (**Pl. 5**). In the Wyoming Water Framework Plan, the

Aspen Shale was classified as a major confining unit [major aquitard] (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**). Because shale is the predominant lithology, the Aspen Shale is classified as a confining unit herein (**Pl. 5**); however, it is recognized that water can be obtained locally from the Aspen confining unit in areas where discontinuous sandstone beds or zones with fractures are present (Lines and Glass, 1975, Sheet 1; Richter et al., 1981, Table IV-1). Few hydrogeologic data were located as part of this study, but one measurement of porosity (15 percent) from petroleum exploration was inventoried for the Aspen confining unit (**Pl. 4**).

Chemical characteristics

The chemical composition of groundwater in the Aspen confining unit in the Bear River Basin was characterized and the quality evaluated on the basis of two produced-water samples. Constituent concentrations are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram C**). The TDS concentrations (28,300 mg/L and 31,000 mg/L) indicated the water was very saline and likely was unusable for all purposes. Health-based standards (USEPA MCLs and HALs) were not applicable for any of the constituents analyzed in the produced-water samples. Concentrations of TDS and chloride in both samples exceeded aesthetic standards (USEPA SMCLs of 500 mg/L and 250 mg/L, respectively) for domestic use, as well as State of Wyoming agricultural and livestock-use standards (WDEQ Class II standards of 2,000 mg/L and 100 mg/L, respectively, and WDEQ Class III standards of 5,000 mg/L and 2,000 mg/L, respectively). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in both produced-water samples.

7.3.6 Wayan Formation

The Upper and Lower Cretaceous Wayan Formation (**Pl. 5**) consists of variegated mudstone, siltstone, and sandstone (Love et al., 1993, Sheet 2). No data were located describing the physical and chemical characteristics of the lithostratigraphic unit in the Bear River Basin.

7.3.7 Quealy Formation

The Upper and Lower Cretaceous Quealy Formation (**Pl. 5**) is about 1,000-ft thick northeast of the town of Cokeville and consists of red and variegated pastel-tinted mudstone and minor interbedded pink, gray, and tan sandstone (Rubey, 1973; Lines and Glass, 1975). The formation thins southward and is absent to the east and south of the town of Cokeville (Rubey, 1973). The Quealy Formation thins eastward from about 1,100 ft in Idaho to about 500 ft in Wyoming (Oriel and Platt, 1980; Rubey et al., 1980). The Quealy Formation is the western stratigraphic equivalent of the middle to lower part of the Aspen Shale (Rubey, 1973). In general, the underlying Cokeville Formation thickens to the south. South of the latitude of Cokeville, where the Quealy Formation is absent, the Sage Junction Formation directly overlies the Cokeville Formation (Rubey, 1973). No data were located describing the physical and chemical characteristics of the lithostratigraphic unit.

7.3.8 Cokeville Formation

The Lower Cretaceous Cokeville Formation (**Pl. 5**) consists of gray to tan fossiliferous sandstone, sandy siltstone, and light to dark gray claystone/mudstone with minor fossiliferous tan limestone; light gray, tan, and pink porcellanite; bentonite; and a few coal beds (Rubey, 1973; Lines and Glass 1975; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The coal beds are located in the upper part of the Cokeville Formation; these coal beds were mined about one-half mile west of Sage (Rubey, 1973). In the Sage area, the Cokeville Formation ranges from 1,900- to 2,500-ft thick (Rubey, 1973). The Cokeville Formation thickens southeastward from about 850 ft in Idaho to about 3,000 ft in Wyoming (Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The upper part of the Cokeville Formation is the western stratigraphic equivalent of the lower part of the Aspen Shale, and the lower part of the formation is the western stratigraphic equivalent to the upper Bear River Formation (Rubey, 1973). No data were located describing the physical and

chemical characteristics of the lithostratigraphic unit.

7.3.9 Bear River aquifer

The physical and chemical characteristics of the Bear River aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics
The Lower Cretaceous Bear River Formation consists of fissile black shale interbedded with brown fine-grained sandstone, and minor interbedded fossiliferous limestone and bentonite. Thickness of the formation in the Overthrust Belt ranges from about 650 to 1,800 ft (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993).

Previous investigators have classified the Bear River Formation as an aquifer, and that definition is retained herein (**Pl. 5**). Berry (1955) identified the Bear River Formation as a potential aquifer in the Cokeville area. Robinove and Berry (1963, Plate 1) speculated that the Bear River Formation in the Bear River valley "possibly may yield small amounts of water." Lines and Glass (1975, Sheet 1) noted that "small quantities" of water were available from the discontinuous sandstone beds in the formation. In the Overthrust Belt, the Bear River Formation was identified as either a "discontinuous aquifer with local confining beds" or "minor aquifer" by Ahern et al. (1981, Figure II-7, and Table IV-1) (**Pl. 5**). Interbedded discontinuous sandstone beds compose the aquifer (Ahern et al., 1981; Lines and Glass, 1975, Sheet 1). In the Wyoming Water Framework Plan, the Bear River Formation was classified as a marginal aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**). Few hydrogeologic data are available, but one discharge measurement (100 gal/min) was inventoried for a spring issuing from the Bear River aquifer (**Pl. 4**).

Chemical characteristics
The chemical composition of groundwater in the Bear River aquifer in the Bear River Basin was characterized and the quality evaluated on the

basis of one environmental water sample from one spring. Individual constituent concentrations are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, diagram K**).The TDS concentration (386 mg/L) indicated that the water was fresh. On the basis of the few properties and constituents analyzed for in the environmental water sample, the quality of water from Bear River aquifer in the Bear River Basin was likely suitable for most uses. No concentrations of properties or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Bear River aquifer in the Bear River Basin also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram D**).The TDS concentration (1,150 mg/L) indicated that the water was slightly saline. Chemical analyses for few properties and constituents were available for the one produced-water sample; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. Nonetheless, concentrations of one property in the Bear River aquifer in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. None of the constituents analyzed had applicable health-based standards; however, the concentration of TDS exceeded aesthetic standards (USEPA SMCL of 500 mg/L) for domestic use. None of the concentrations of properties or constituents exceeded State of Wyoming agricultural- and livestock-use standards.

7.3.10 Thomas Fork aquifer

The physical and chemical characteristics of the Thomas Fork aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics

The Thomas Fork aquifer is composed of the Lower Cretaceous Thomas Fork Formation (**Pl. 5**). The Thomas Fork Formation consists of variegated, banded, red, purple, brown, and green mudstone and minor interbedded gray to tan sandstone (Rubey, 1973; Lines and Glass 1975; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). In part, the sandstone is conglomeratic with sediments (pebbles and cobbles) as large as 4 inches in diameter, and the mudstone contains gray to brown limestone nodules as large as several inches in diameter (Rubey, 1973). The formation thickens northward to about 2,000-ft thick in the southwestern part of Star Valley, and thins southward to about 350-ft thick in the Sage area (Rubey, 1973; Oriel and Platt, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The formation merges to the south with and is lithologically indistinguishable from the upper part of the Early Cretaceous-age Kelvin Formation in northeastern Utah (Dover and M'Gonigle, 1993).

Most information about the physical and chemical characteristics of the Thomas Fork aquifer was obtained through installation and subsequent testing of three wells completed in the aquifer to replace three springs as the water supply for the town of Cokeville (Forsgren Associates, Inc., 1993a, b; TriHydro Corporation, 1993, 2002, 2003). The Thomas Fork Formation is classified as an aquifer in the Bear River Basin herein based on these investigations. In fact, previous descriptions of the hydrogeologic characteristics of the Thomas Fork Formation were very limited. Lines and Glass (1975, Sheet 1) speculated that sandstone beds in the Thomas Fork Formation may yield "small quantities" of water to wells.

TriHydro Corporation (2002) summarized all information obtained from drilling, installation, and testing of the three wells completed in the Thomas Fork aquifer to supply water for the town of Cokeville. One of the three wells was a test well and the other two wells were completed at depths of about 141 and 174 ft below land surface as production wells (Cokeville #2 and Cokeville #3) for the town. The investigators (TriHydro

Corporation, 2002, p. 3-7) reported that sandstone beds composing the aquifer typically were well cemented with calcite cement, and typically have poor intergranular porosity in "an unweathered and unfractured condition." Porosity and permeability were attributed to fractures in the sandstone beds composing the aquifer. Based on interpretation of aquifer tests conducted on both production wells, the investigators concluded that the Thomas Fork aquifer was a semiconfined, fracture-flow aquifer with primarily conduit flow. A hydraulic gradient of 0.073 foot per foot was calculated for the aquifer using water levels measured in all three wells. Using this hydraulic gradient, an estimated porosity of 17 percent, and a hydraulic conductivity estimate obtained from the aquifer tests, TriHydro Corporation (2002) estimated the average groundwater-flow velocity for the Thomas Fork aquifer in the area to be 22.6 ft/d.

The investigators (TriHydro Corporation, 2002, p. 3-10) also conceptually described potential sources of recharge to the aquifer in the area where both wells were installed. Potential sources of recharge identified were (1) streamflow losses along Pine, Spring, and Sublette Creeks and direct infiltration of precipitation and seepage to overlying lithostratigraphic units (Quaternary alluvial, terrace, and loess deposits, and the Tertiary-age Fowkes Formation) and subsequent movement of water in these units downward into the underlying Thomas Fork aquifer; and (2) direct infiltration of precipitation (rain and snow) on Thomas Fork aquifer outcrop areas.

Hydrogeologic data describing the Thomas Fork aquifer in the Bear River Basin, including spring-discharge and well-yield measurements, and other hydraulic properties, are shown on **Plate 3** and summarized on **Plate 4**. Two measurements of discharge for springs issuing from the Thomas Fork were available and were 0.2 and 0.5 gal/min. Yields from wells completed in Thomas Fork aquifer ranged from 250 to 747 gal/min, with a median of 653 gal/min (**Pl. 4**). Specific capacities ranged from 8.9 to 51 (gal/min)/ft with a median of 12 (gal/min)/ft (**Pl. 4**). Estimates of transmissivity using all methods for wells completed in the Thomas Fork aquifer ranged from 5,210 to 18,800 ft²/d,

with a median of 8,060 ft²/d (**Pl. 4**). Estimates of hydraulic conductivity for wells completed in the Thomas Fork aquifer ranged from 34 to 210 ft/ per day, with a median of 56 ft/d (**Pl. 4**).

Chemical characteristics

The chemical composition of groundwater in the Thomas Fork aquifer in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from one well [and one spring (only specific conductance is available for the spring sample)]. Individual constituent concentrations are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, diagram L**). The TDS concentration (390 mg/L) indicated that the water was fresh (**Appendix E; Appendix G, Diagram L**). On the basis of the few properties and constituents analyzed for in the environmental water sample, the quality of water from Thomas Fork aquifer in the Bear River Basin was suitable for most uses. No concentrations of properties or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

7.3.11 Smiths Formation

The Lower Cretaceous Smiths Formation is composed of ferruginous black shale and interbedded tan, quartz-rich, very fine-grained sandstone. Thickness of the Smiths Formation is about 750 ft along the Smiths Fork located to the northeast of the town of Cokeville (Rubey, 1973; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The black shale and tan sandstone are interbedded throughout the formation, but the upper unnamed member primarily is tan sandstone, and the lower unnamed member primarily is black shale (Rubey, 1973; Rubey et al., 1980). The Smiths Formation thins southward to about 300 to 400 ft in thickness near the Sage and Kemmerer areas, and to about 115 to 200 ft in the Evanston area (M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The Smiths Formation thickens eastward from about 300 ft in Idaho to about 850 ft in Wyoming (Oriel and Platt, 1980; Rubey et al., 1980). No data were located describing the physical and chemical characteristics of the lithostratigraphic unit.

7.3.12 Gannett aquifer and confining unit

The physical and chemical characteristics of the Gannett aquifer and confining unit in the Bear River Basin are described in this section of the report.

Physical characteristics

The Gannett aquifer and confining unit is composed of the Lower Cretaceous Gannett Group. The Gannett Group consists of red sandy mudstone, sandstone, and chert-pebble conglomerate. Some thin limestone and dark gray shale are present in the upper part of the unit, and the lower part is more conglomeratic. Thickness of the Gannett Group decreases from about 3,000 ft in Idaho to about 800 ft in Wyoming (Lines and Glass 1975; Oriel and Platt, 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). In the Cokeville area of Lincoln County, the Gannett Group thins southeastward from about 2,900 to 790 ft (Rubey et al., 1980). The Gannett Group is as much as 2,100-ft thick above and to the west of the Absaroka thrust fault, and thins eastward to about 650 ft below and to the east of the Absaroka thrust fault in the Kemmerer area (M'Gonigle and Dover, 1992).

In some areas, the Gannett Group is mapped as separate formations or groups of formations. The Gannett Group was described in detail by Eyer (1969) and Furer (1967, 1970). The Gannett Group is composed of five formations (in descending order from top to bottom): Smoot Formation, Draney Limestone, Bechler Conglomerate, Peterson Limestone, and Ephraim Conglomerate.

The Smoot Formation of the Gannett Group was described as the unnamed upper redbed member until named by Eyer (1969). The formation is composed of interbedded red mudstone and siltstone (Oriel and Platt, 1980). The Smoot Formation is absent in some local areas and is about 200 ft-thick when combined with the underlying Draney Limestone (Oriel and Platt, 1980).

The Draney Limestone of the Gannett Group consists of dark to medium gray limestone, weathering light gray, very fine-crystalline to aphanitic and interbedded with dark gray calcareous shale and siltstone (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980). The unit is about 200-ft thick when combined with the overlying Smoot Formation.

The Bechler Conglomerate of the Gannett Group is composed of red, red-gray, purple, and purple-gray, calcareous mudstone and siltstone, which becomes increasingly sandstone and chert-pebble conglomerate towards the west (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980). A few thin limestone interbeds occur locally. The formation is about 1,300-ft thick.

The Peterson Limestone of the Gannett Group consists of light to medium gray and pastel-colored, weathering very light gray, very fine-crystalline limestone and pastel-colored calcareous mudstone (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980). The unit is about 230-ft thick.

The basal Ephraim Conglomerate of the Gannett Group is composed of brick-red, red, orange-red, and maroon mudstone and siltstone; light gray, red, tan, and brown, crossbedded, coarse-grained calcareous to quartzitic sandstone; and red to brown, chert-pebble conglomerate. Thickness of the Ephraim Conglomerate decreases eastward from about 3,300 ft in Idaho to about 490 ft in Wyoming (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992).

Permeability in the Gannett Group likely is small on a regional scale, and thus, in most areas the unit is capable of yielding only small quantities of water locally. However, more permeable water-bearing parts of the Gannett Group capable of yielding larger quantities of water are present in the conglomeratic formations (Bechler and Ephraim Conglomerates) and in areas where fractures and secondary permeability (solution openings) are present (Robinove and Berry, 1963; Lines and Glass, 1975, Sheet 1; Ahern et al.,

1981, Table IV-1). In addition, sandstone beds in the lower part of the Gannett Group also may be permeable and water-bearing (Ahern et al., 1981, Table IV-1). Ahern et al. (1981, Figure II-7) classified the Gannett Group as a series of "discontinuous aquifers with local confining units" in the Overthrust Belt and the adjacent Green River Basin (**Pl. 5**). Glover (1990) considered the Ephraim Conglomerate of the Gannett Group (identified as a conglomerate near the base of the Gannett Group) to be a minor aquifer in the Bear River valley in the Evanston area. He also noted that aquifers in the Gannett Group were hydraulically isolated from the overlying Evanston aquifer (Hams Fork Conglomerate Member of the Evanston Formation), Wasatch aquifer, and Bear River alluvial aquifer. TriHydro Corporation (1993, p. II-3) reported that the Ephraim Conglomerate produced about 10 gal/min during drilling of a test boring at an anticline in the vicinity of Spring Creek near Cokeville. In the Wyoming Water Framework Plan, the Gannett Group was classified as a marginal aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**). Because the unit has low overall permeability, but with distinct zones and formations of higher permeability with potential to yield water to wells, the Gannett Group was classified as both an aquifer and confining unit herein (**Pl. 5**).

Hydrogeologic data describing the Gannett aquifer and confining unit in the Bear River Basin, including spring-discharge and well-yield measurements, and other hydraulic properties, are shown on **Plate 3** and summarized on **Plate 4**. Measured discharges of springs issuing from the Gannett aquifer and confining unit ranged from 0.25 to 800 gal/min with a median of 20 gal/min (**Pl. 4**). Two measurements of well yield were available and were 30 and 200 gal/min (**Pl. 4**). One estimate of transmissivity obtained from petroleum exploration was inventoried and was 0.08 ft²/d (**Pl. 4**).

Chemical characteristics
The chemical composition of groundwater in the Gannett aquifer and confining unit in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water

samples from two wells and six springs. Summary statistics calculated for available constituents are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram M**).TDS concentrations indicated that waters were fresh (**Appendix E; Appendix G, Diagram M**). TDS concentrations ranged from 243 to 854 mg/L, with a median of 376 mg/L.

Concentrations of some properties and constituents in the Gannett aquifer and confining unit in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one property and one constituent exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (one of six samples exceeded the SMCL of 500 mg/L) and fluoride (one of six samples exceeded the SMCL of 2 mg/L).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the Bear River Basin. The property and constituent in environmental water samples that had concentrations greater than agricultural-use standards were SAR (one of three samples exceeded the WDEQ Class II standard of eight) and chloride (one of six samples exceeded the WDEQ Class II standard of 100 mg/L). No properties or constituents had concentrations that exceeded State of Wyoming livestock standards.

7.3.13 Stump Formation

The Upper to Middle Jurassic Stump Formation consists of interbedded light to dark green, green-gray, glauconitic, fine-grained sandstone, siltstone, and limestone (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). Pipiringos and Imlay (1979) divided the Stump Formation into two members—the Upper Jurassic Redwater Member and the Middle Jurassic Curtis

Member. The Stump Formation ranges in thickness from 92 ft to at least 400 ft in the Overthrust Belt area, and thins irregularly to the north and east from the thickest section in southeastern Idaho (Pipiringos and Imlay, 1979; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). The upper member of the Stump Formation is similar to the silty to sandy facies of the Redwater Member of the Sundance Formation eastward in Wyoming, whereas the lower member is similar to the Curtis Formation in the San Rafael Swell area of central Utah (Pipiringos and Imlay, 1979). Individual members are not shown on **Plate 5**.

The Redwater Member of the Stump Formation consists of two lithologic units (Pipiringos and Imlay, 1979). The upper lithologic unit is composed of gray, green-gray, nearly white, glauconitic, thin- to thick-bedded, crossbedded sandstone with minor interbeds of sandy siltstone, clayey siltstone, and oolitic, sandy limestone, which locally contains chert pebbles, belemnite fossils, and ammonite fossils. The lower lithologic unit is composed of yellow-gray to brown, glauconitic siltstone and claystone, which is locally sandy and contains belemnite fossils.

The Curtis Member of the Stump Formation consists of two lithologic units (Pipiringos and Imlay, 1979). The upper lithologic unit is composed of green-gray to olive-green, soft, flaky to fissile claystone with minor thin interbeds of sandstone and oolitic, fossiliferous limestone. The lower lithologic unit is composed of green-gray to brown-gray, glauconitic, thin- to thick-bedded, ripple-marked, crossbedded, fine- to very fine-grained sandstone (some silty and medium-grained sandstone).

Little information is available describing the hydrogeologic characteristics of the Stump Formation. In the Bear River valley, Robinove and Berry (1963, Plate 1) speculated that the Stump Formation was likely to yield small quantities of groundwater to wells. Lines and Glass (1975, Sheet 1) noted that rocks in the Stump Formation were relatively impermeable and in most areas were probably capable of yielding only small quantities

of water. Ahern et al. (1981, Figure II-7) classified the Stump Formation as a confining unit [aquitard] or poor aquifer (**Pl. 5**). No data were located describing the physical and chemical characteristics of the hydrogeologic unit.

7.3.14 Preuss Sandstone or Redbeds

The physical and chemical characteristics of the Preuss Sandstone or Redbeds in the Bear River Basin are described in this section of the report.

Physical characteristics
The Middle Jurassic Preuss Sandstone or Redbeds (**Pl. 5**) consists of interbedded purple, maroon, dull red, purple-gray, and red-gray, siltstone, sandy siltstone, silty claystone, and claystone with minor interbedded halite (rock salt), alum, and gypsum locally present in irregular zones (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992; Dover and M'Gonigle, 1993). Beds of red, gray, and tan, fine-grained, thin-bedded and regular-bedded sandstone also are present. Formation thickness decreases eastward from about 1,640 ft in Idaho to 360 ft in Wyoming (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey et al., 1980). The Preuss Sandstone or Redbeds are overlain by the Stump Formation and underlain by the Twin Creek Limestone (**Pl. 5**).

Little information is available describing the hydrogeologic characteristics of the Preuss Sandstone or Redbeds. In the Bear River valley, Robinove and Berry (1963, Plate 1) speculated that the Preuss Sandstone or Redbeds were likely to yield small quantities of groundwater to wells. Lines and Glass (1975, Sheet 1) noted that rocks in the Preuss Sandstone or Redbeds were relatively impermeable and in most areas were probably capable of yielding only small quantities of water. Ahern et al. (1981, Figure II-7) classified the formation as a confining unit [aquitard] or poor aquifer (**Pl. 5**).

 In outcrop and shallow groundwater areas, bedded halite (rock salt) in the lower part of the formation has been removed by dissolution (Imlay, 1952). In areas where evaporite beds have been removed by

dissolution, breccia zones and collapse structures may have formed and consequently, may have increased permeability.

Few hydrogeologic data are available, but five measurements of discharge for springs issuing from the Preuss Sandstone or Redbeds were inventoried as part of this study. Spring discharge measurements ranged from 0.1 to 50 gal/min with a median of 2 gal/min. (**Pl. 4**).

Chemical characteristics
The chemical composition of groundwater in the Preuss Sandstone or Redbeds in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations in the environmental water samples are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram N**). Both TDS concentrations (664 and 715 mg/L) indicated that the water was slightly saline (**Appendix E; Appendix G, Diagram N**).

On the basis of the few properties and constituents analyzed for in the environmental water samples, the quality of water from the Preuss Sandstone or Redbeds in the Bear River Basin was likely suitable for most uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of one property in both samples exceeded aesthetic standards for domestic use: TDS (USEPA SMCL of 500 mg/L). One constituent (chloride) had concentrations greater than State of Wyoming agricultural-use standards (WDEQ Class II standard of 100 mg/L) in both samples. No concentrations of properties or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.3.15 Twin Creek aquifer

The physical and chemical characteristics of the Twin Creek aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics

The Twin Creek aquifer is composed of the Middle Jurassic Twin Creek Limestone (**Pl. 5**). The Twin Creek Limestone consists of green-gray argillaceous (shaly) limestone and calcareous siltstone. Thickness of the formation decreases eastward from about 3,300 ft in Idaho to about 440 ft in Wyoming (Imlay, 1967; Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992). The formation is as much as 2,900-ft thick above and to the west of the Absaroka thrust fault. Thickness of the Twin Creek Limestone below and to the east of the Absaroka thrust fault in the Kemmerer area ranges from 800 to 1,000 ft (M'Gonigle and Dover, 1992). The Twin Creek Limestone was deposited in a Jurassic seaway marine environment, as reflected by the presence of pelecypod fossils such as *Gryphaea* (Imlay, 1967). Imlay (1967) defined and described seven members of the Twin Creek Formation in the Overthrust Belt of Wyoming-Idaho-Utah. These members are, from youngest (top) to oldest (bottom): Giraffe Creek Member, Leeds Creek Member, Watton Canyon Member, Boundary Ridge Member, Rich Member, Sliderock Member, and Gypsum Spring Member. Individual members are not shown on **Plate 5**.

The Giraffe Creek Member of the Twin Creek Limestone consists of yellow-gray, green-gray, and pink-gray, silty to sandy, ripple-marked, thin-bedded limestone and sandstone with minor thick interbeds of oolitic sandy limestone. Sand and glauconite content increases to the west, and the Giraffe Creek Member of the Twin Creek Limestone grades upward into red, soft siltstone at the base of the Preuss Sandstone or Redbeds. Thickness decreases eastward and northward from 295 to 25 ft (Imlay, 1967).

The Leeds Creek Member of the Twin Creek Limestone consists of light gray, dense, shaly, soft limestone, which weathers into slender splinters, and minor interbeds of oolitic silty or sandy, ripple-marked limestone. Clay content increases to the northeast in Idaho and Wyoming and to the south in Utah. The Leeds Creek Member is the least resistant member of the Twin Creek Limestone and commonly forms valleys in outcrop areas. The Leeds Creek Member of the Twin Creek Limestone

grades upward into the harder, silty to sandy, basal limestone of the overlying Giraffe Creek Member. Thickness decreases eastward from about 1,600 to 260 ft (Imlay, 1967).

The Watton Canyon Member of the Twin Creek Limestone consists of gray, compact, dense, brittle, medium- to thin-bedded limestone, which forms prominent cliffs and ridges. The basal unit of the Watton Canyon Member generally is massive and oolitic, and some oolitic limestone interbeds occur throughout the unit. The upper part of the Watton Canyon Member grades upward into the shaly, soft basal limestone of the overlying Leeds Creek Member and contains pelecypod fossils. Thickness of the Watton Canyon Member decreases eastward from about 400 to 60 ft (Imlay, 1967).

The Boundary Ridge Member of the Twin Creek Limestone consists of red, green, and yellow, soft siltstone with interbedded silty to sandy or oolitic limestone. The Boundary Ridge Member grades eastward into red, gypsiferous, soft siltstone and claystone, and grades westward into cliff-forming, oolitic to dense limestone with minor interbedded red siltstone. The Boundary Ridge Member is overlain by the cliff-forming, basal limestone of the Watton Canyon Member. Thickness decreases eastward from about 285 to 30 ft (Imlay, 1967).

The Rich Member of the Twin Creek Limestone consists of gray, shaly limestone that is very soft at the base; clay content increases to the north, and the upper part grades into the basal hard sandy limestone or red, soft siltstone of the Boundary Ridge Member of the Twin Creek Limestone. Pelecypod and cephalopod fossils are present. Thickness of the Rich Member decreases eastward from 500 to 40 ft (Imlay, 1967).

The Sliderock Member of the Twin Creek Limestone consists of gray-black, medium- to thin-bedded limestone with oolitic basal beds, and commonly forms a low ridge between adjacent members. Pelecypod and cephalopod fossils are present. Thickness of the Sliderock Member decreases eastward from 285 to 20 ft (Imlay, 1967).

The Gypsum Spring Member of the Twin Creek Limestone consists of red to yellow, soft siltstone and claystone, interbedded with brecciated, vuggy, or chert-bearing limestone. In Wyoming, a basal unit of brecciated limestone is present and grades eastward into thick, massive gypsum deposits. The chert-bearing limestone thickens westward from a few feet thick in Wyoming to a thick, cliff-forming unit in Idaho. Locally, the top bed of the Gypsum Spring Member is a green tuff. Thickness of the Gypsum Spring Member decreases eastward from 400 to 12 ft (Imlay, 1967). In areas of Wyoming located east of the Bear River Basin, the Gypsum Spring Member of the Twin Creek Limestone has been elevated to formation rank and is referred to as the Gypsum Spring Formation.

The Twin Creek Limestone is classified as an aquifer or potential aquifer by investigators and that classification is retained herein (**Pl. 5**). In the Bear River valley, Robinove and Berry (1963, Plate 1) speculated that the Twin Creek Limestone was likely to yield small quantities of groundwater to wells. Lines and Glass (1975, Sheet 1) noted that permeability in the upper part of the Twin Creek Limestone likely was low compared to the lower part and thus, the formation likely would yield small quantities of water to wells completed in the upper part of the unit. The investigators noted that limestone in the lower part of the Twin Creek Limestone is brecciated and honeycombed; thus, wells completed in the lower part of the formation were more likely to yield moderate quantities of water (Lines and Glass, 1975, Sheet 1). In the Wyoming Water Framework Plan, the Twin Creek Limestone was classified as a minor aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**).

The Twin Creek aquifer likely is in hydraulic connection with the underlying Nugget aquifer (Lines and Glass, 1975, Plate 1; Ahern et al., 1981). In fact, Lines and Glass (1975, Sheet 1) noted that few springs issue from the lower part of the Twin Creek Limestone, possibly because the overlying unit may be in hydraulic connection with, and "drain into" the underlying Nugget aquifer. Clarey (2011) speculated that groundwater from the Gypsum Spring Member in areas where gypsum deposits are present may have the potential

for calcium-sulfate-type waters and large TDS concentrations.

Hydrogeologic data describing the Twin Creek aquifer, including spring-discharge measurements and other hydraulic properties, are shown on **Plate 3** and summarized on **Plate 4**. Two measured discharges of springs issuing from the Twin Creek aquifer were 15 and 25 gal/min (**Pl. 4**). Porosity estimates obtained from petroleum exploration ranged from 0.65 to 3.8 percent (**Pl. 4**). Permeability estimates obtained from petroleum exploration ranged from 0.005 to 1.9 millidarcies (**Pl. 4**).

Chemical characteristics

The chemical composition of groundwater in the Twin Creek aquifer in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations in the environmental water samples are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram O**). The TDS concentrations (282 and 366 mg/L) indicated that the water was fresh. On the basis of the few properties and constituents analyzed for in the environmental water samples, the quality of water from Twin Creek aquifer in the Bear River Basin was likely suitable for most uses. On the basis of comparison of concentrations with health-based standards (USEPA MCLs and HALs), all water was suitable for domestic use. Concentrations of two constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use in one sample: iron (SMCL of 300 μg/L) and manganese (SMCL of 50 μg/L). No concentrations of properties or constituents approached or exceeded applicable State of Wyoming agriculture, or livestock water-quality standards.

The chemical composition of groundwater also was characterized and the quality evaluated on the basis of seven produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram E**). TDS concentrations from produced-water samples

indicated that most waters were briny (71 percent of samples) and the remaining water was very saline (**Appendix F; Appendix H, Diagram E**). TDS concentrations ranged from 31,100 to 329,000 mg/L, with a median of 137,000 mg/L. Most available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards for domestic use: TDS (all 7 samples exceeded the SMCL of 500 mg/L), chloride (all 7 samples exceeded the SMCL of 250 mg/L), sulfate (all 7 samples exceeded the SMCL of 250 mg/L), and pH (2 of 7 samples below lower SMCL limit of 6.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in all 7 produced-water samples.

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (all 7 samples exceeded the WDEQ Class II standard of 2,000 mg/L), chloride (all 7 samples exceeded the WDEQ Class II standard of 100 mg/L), and sulfate (all seven samples exceeded the WDEQ Class II standard of 200 mg/L). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (all seven samples exceeded the WDEQ Class III standard of 5,000 mg/L), chloride (all seven samples exceeded the WDEQ Class III standard of 2,000 mg/L), sulfate (three of seven samples exceeded the WDEQ Class III standard of 3,000 mg/L), and pH (two of seven samples below lower WDEQ Class III limit of 6.5).

7.3.16 Nugget aquifer

The physical and chemical characteristics of the Nugget aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics

The Nugget aquifer is composed of the Triassic (?) to Jurassic (?) Nugget Sandstone (**Pl. 5**). The Nugget Sandstone consists of tan to pink, crossbedded, well-sorted, quartz-rich sandstone. Thickness of the Nugget Sandstone ranges from about 600 ft to more than 1,000 ft (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992). In the Kemmerer area, the formation is as much as 1,475-ft thick west of the Absaroka thrust fault and about 650-ft thick east of the Absaroka thrust fault (M'Gonigle and Dover, 1992). Age of the Nugget Sandstone is uncertain, but the unit is possibly Triassic to Jurassic in age (Love et al., 1993) (**Pl. 5**). The lower part of the formation may be Triassic but the lack of diagnostic fossils in the sandstone has made the age of the formation uncertain. The Nugget Sandstone has been interpreted as deposited as an eolian (wind-blown) sand dune sequence from a desert or a beach environment.

The Nugget Sandstone is classified as an aquifer by all investigators and that classification is retained herein (**Pl. 5**). Robinove and Berry (1963, Plate 1) speculated that the Nugget Sandstone was likely to yield small quantities of groundwater to wells in the Bear River valley. Lines and Glass (1975, Sheet 1) considered the Nugget Sandstone to be the "best aquifer" in their "hydrogeologic division 4" (identified as being composed of Jurassic- and Cretaceous-age sandstones and limestones and shown on **Plate 5**) in the Overthrust Belt. The investigators (Lines and Glass, 1975, Sheet 1) reported that the Nugget aquifer was capable of yielding moderate to large quantities of water where "outcrop or recharge areas are large, where bedding is continuous and not offset by faults, and in topographic lows where large thickness of sandstone is saturated." Furthermore, the investigators (Lines and Glass, 1975, Sheet 1) noted that few springs issue from the lower part of the Twin Creek Limestone, possibly because the overlying unit may be in hydraulic connection with, and "drain into" the underlying Nugget aquifer. Springs commonly issue from the Nugget aquifer in the Overthrust Belt (Lines and Glass, 1975, Sheet 1). In the Wyoming Water Framework Plan, the Nugget Sandstone was classified as a

major aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**).

Ahern et al. (1981, Figure II-7, and Table IV-1) classified the Nugget Sandstone as a major aquifer in the Overthrust Belt and the adjacent Green River Basin (**Pl. 5**). The Nugget aquifer was considered to be part of an aquifer system, identified as the Nugget aquifer system, composed of the overlying Twin Creek Limestone and the underlying Ankareh Formation and Thaynes Limestone (**Pl. 5**). The investigators noted that porosity and permeability in the Nugget aquifer were "good," especially in the crossbedded upper part. The investigators also speculated that smaller transmissivities for the Nugget aquifer in the adjacent Green River Basin may be attributable to increased lithostatic pressure (deeper burial) and decreased fracture occurrence.

Clarey (2011) noted that the upper part of the Nugget Sandstone in some areas of the Overthrust Belt has calcite (calcium carbonate) cement with slightly increased permeability, and that the lower part of the formation has siliceous (quartz) cement with decreased permeability. The investigator reported that this "dual cementation feature" of the Nugget Sandstone has been observed in an oilfield production well located to the northeast of Evanston in Uinta County, Wyoming.

Hydrogeologic data describing the Nugget aquifer in the Bear River Basin, including spring-discharge and well-yield measurements, and other hydraulic properties, are shown on **Plate 3** and summarized on **Plate 4**. Measured discharges of springs issuing from the Nugget aquifer ranged from 2 to 300 gal/min with a median of 5 gal/min (**Pl. 4**). Estimates of transmissivity obtained from petroleum exploration for wells completed in the Nugget aquifer ranged from 0.25 to 8.84 ft²/d, with a median of 4.36 ft²/d (**Pl. 4**). Porosity estimates obtained from petroleum exploration ranged from 2 to 22 percent (**Pl. 4**). Permeability estimates obtained from petroleum exploration ranged from 0.01 to 1,400 millidarcies (**Pl. 4**).

Chemical characteristics

The chemical composition of groundwater in

the Nugget aquifer in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from six springs. Summary statistics calculated for available constituents are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram P**). TDS concentrations indicated that waters were fresh (**Appendix E; Appendix G, Diagram P**). TDS concentrations ranged from 54 to 824 mg/L, with a median of 210 mg/L.

The chemical composition of groundwater in the Nugget aquifer in the Bear River Basin was also characterized and the quality evaluated on the basis of 14 produced-water samples from wells. Summary statistics calculated for available constituents are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram F**). TDS concentrations from produced waters were variable and indicated that waters were very saline (50 percent of samples) or briny (**Appendix F; Appendix H, Diagram F**). TDS concentrations ranged from 14,100 to 113,000 mg/L, with a median of 33,500 mg/L.

Concentrations of some properties and constituents in water from the Nugget aquifer in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards (USEPA MCLs and HALs). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (one of five samples exceeded the SMCL of 500 mg/L), sulfate (one of five samples exceeded the SMCL of 250 mg/L), and pH (one of six samples below lower SMCL limit of 6.5).

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use

standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (all 14 samples exceeded the SMCL of 500 mg/L), chloride (all 14 samples exceeded the SMCL of 250 mg/L), iron (all three samples exceeded the SMCL of 300 µg/L), sulfate (all 14 samples exceeded the SMCL of 250 mg/L), and pH (five of 14 samples below lower SMCL limit of 6.5). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in all 14 of produced-water samples.

Concentrations of some properties and constituents exceeded State of Wyoming standards in the Bear River Basin. The constituent in environmental water samples measured at concentrations greater than agricultural-use standards was sulfate (one of five samples exceeded the WDEQ Class II standard of 200 mg/L). Values of one property (pH) exceeded livestock-use standards and (one of six samples below lower WDEQ Class III limit of 6.5).

The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (all 14 samples exceeded the WDEQ Class II standard of 2,000 mg/L), chloride (all 14 samples exceeded the WDEQ Class II standard of 100 mg/L), iron (all three samples exceeded the WDEQ Class II standard of 5,000 mg/L5,000 µg/L), sulfate (all 14 samples exceeded the WDEQ Class II standard of 200 mg/L), and pH (one of 14 samples below lower WDEQ Class II limit of 4.5). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (all 14 samples exceeded the WDEQ Class III standard of 5,000 mg/L), chloride (all 14 samples exceeded the WDEQ Class III standard of 2,000 mg/L), sulfate (seven of 14 samples exceeded the WDEQ Class III standard of 3,000 mg/L), and pH (five of 14 samples below lower WDEQ Class III limit of 6.5).

7.3.17 Ankareh aquifer

The Upper Triassic Ankareh Formation composes

the Ankareh aquifer (**Pl. 5**). The Ankareh Formation consists of red and maroon shale and pale purple limestone with minor white to red, fine-grained, quartz-rich sandstone; thickness of the formation increases eastward from about 460 ft in Idaho to about 920 ft in Wyoming (Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; M'Gonigle and Dover, 1992). In central Wyoming, the Ankareh Formation is the stratigraphic equivalent of the upper part of the Chugwater Group or Formation (including the Red Peak Member, Alcova Limestone Member, unnamed redbeds of interbedded siltstone and sandstone, and Popo Agie Member of the Chugwater Group or Formation) (Kummel, 1954). The sandstone may correlate westward to the Timothy Sandstone Member of the Thaynes Limestone, and the limestone may correlate westward to the Portneuf Limestone Member of the Thaynes Limestone (Kummel, 1954). Redbeds present below the thin limestone or sandstone in the Ankareh Formation may correlate westward to the Lanes Tongue of the Ankareh Formation (Kummel, 1954).

Previous investigators have defined the Ankareh Formation as an aquifer, and that definition is tentatively retained herein (**Pl. 5**). In the Bear River valley, Robinove and Berry (1963, Plate 1) speculated that the Ankareh Formation was likely to yield small quantities of groundwater to wells. Lines and Glass (1975, Sheet 1) noted that rocks in the Ankareh Formation were relatively impermeable in most areas, but that the unit was probably capable of yielding small quantities of water locally. Ahern et al. (1981, Figure II-7, and Table IV-1) defined the Ankareh Formation as a minor aquifer or minor regional aquifer (locally confining) in the Overthrust Belt (**Pl. 5**). No data were located describing the physical and chemical characteristics of the hydrogeologic unit in the Bear River Basin..

7.3.18 Thaynes aquifer

The physical and chemical characteristics of the Thaynes aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics

The Thaynes aquifer is composed of the Upper and Lower Triassic Thaynes Limestone (**Pl. 5**). The Thaynes Limestone consists of gray limestone and brown-weathering, gray, calcareous siltstone with abundant dark gray shale and limestone abundant in the lower part of the formation (Lines and Glass 1975; Oriel and Platt, 1980; M'Gonigle and Dover, 1992). Thickness of the Thaynes Limestone decreases eastward from about 1,640 ft in Idaho to about 700 ft in Wyoming.

Kummel (1954) defined several members of the Thaynes Limestone and the interfingering Ankareh Formation, which the investigator considered a member of the Thaynes Limestone. The Timothy Sandstone Member is the uppermost member of the Thaynes Limestone and is missing at Cokeville and at Spring Canyon in Sublette Ridge, Wyoming (Kummel, 1954). This Timothy Sandstone Member is 125-ft thick and consists of red siltstone, shale, and sandstone at Hot Springs along Indian Creek in southeastern Idaho and rapidly thins eastward into Wyoming. In Wyoming, the Timothy Sandstone Member is present in the Grays Range. Individual members are not shown on **Plate 5**.

The Portneuf Limestone Member of the Thaynes Limestone consists of olive-gray, massive limestone and olive-light tan calcareous siltstone, and the unit is 12.5-ft thick at Cokeville Canyon and Spring Canyon in Sublette Ridge, Wyoming (Kummel, 1954). The unit also is present in the Cumberland Gap area south of Kemmerer, Wyoming.

The Lanes Tongue of the Thaynes Limestone consists of red, interbedded shale and siltstone, and the unit is 200-ft thick at Cokeville Canyon and 645-ft thick at Spring Canyon in Sublette Ridge, Wyoming (Kummel, 1954). The redbeds member is similar to the overlying Ankareh Formation (Kummel, 1954). The upper calcareous siltstone member consists of light tan, thin- to massively-bedded, silty limestone and calcareous siltstone that is about 1,000-ft thick at Spring Canyon at Sublette Ridge (Kummel, 1954).

The middle shale member of the Thaynes Limestone consists of black shale and shaly limestone with cephalopod, ammonite, and pelecypod fossils (Kummel, 1954). The middle shale member is about 50-ft thick at Cokeville, Wyoming. The middle limestone member of the Thaynes Limestone consists of gray, massive, fine-crystalline limestone with brachiopod and pelecypod fossils; the unit is about 90-ft thick at Cokeville (Kummel, 1954). The lower shale member of the Thaynes Limestone is composed of dark gray, silty limestone and is about 107-ft thick at Cokeville (Kummel, 1954). The lower limestone member of Thaynes Limestone consists of gray-blue to gray (weathers gray), massive limestone with cephalopod fossils and is about 50-ft thick at Spring Canyon in Sublette Ridge (Kummel, 1954).

Previous investigators have defined the Thaynes Limestone as an aquifer and that definition is retained herein (**Pl. 5**). In the Bear River valley, Robinove and Berry (1963, Plate 1) speculated that the Thaynes Limestone was likely to yield small quantities of groundwater to wells. Lines and Glass (1975, Sheet 1) considered the Thaynes Limestone to be the "best aquifer" in their "hydrogeologic division 3" (identified as being composed of Triassic and Permian siltstones and limestones and shown on **Plate 5**) in the Overthrust Belt. Ahern et al. (1981, Figure II-7, and Table IV-1) defined the Thaynes Limestone as a major aquifer or regional aquifer in the Overthrust Belt. Limestone in the Thaynes aquifer likely yields moderate quantities of water to wells; yields are greatest in areas with bedding-plane partings and where secondary permeability in the form of fractures or solution openings, or both, has developed (Lines and Glass, 1975, Sheet 1; Ahern et al., 1981, Figure II-7, and Table IV-1).

Hydrogeologic data describing the Thaynes aquifer, including spring-discharge and well-yield measurements and other hydraulic properties, are summarized on **Plate 4**. Four measured discharges of springs issuing from the Thaynes aquifer ranged from 20 to 300 gal/min with a median of 47.5 gal/min (**Pl. 4**). Two measurements of yields from flowing wells completed in the Thaynes aquifer (12 and 150 gal/min) were inventoried (**Pl. 4**).

Porosity estimates obtained from petroleum exploration data ranged from 1 to 8 percent (**Pl. 4**). Two permeability estimates were obtained from petroleum exploration data and were 0.1 and 0.2 millidarcies (**Pl. 4**).

Chemical characteristics

The chemical composition of groundwater in the Thaynes aquifer in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from one well and three springs. Summary statistics calculated for available constituents are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram Q**). TDS concentrations indicated that waters were fresh (**Appendix E; Appendix G, Diagram Q**). TDS concentrations ranged from 127 to 386 mg/L, with a median of 299 mg/L. On the basis of the few properties and constituents analyzed for in the environmental water sample, the quality of water from Bear River aquifer and confining unit in the Bear River Basin was likely suitable for most uses. No concentrations of properties or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Thaynes aquifer in the Bear River Basin also was characterized and the quality evaluated on the basis of three produced-water samples from two wells (two of the three samples were from different depth intervals within one of the wells). Individual constituent concentrations for this sample are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram G**). The TDS concentrations indicated that the waters were briny (**Appendix F; Appendix H, Diagram G**). TDS concentrations ranged from 36,600 to 72,600 mg/L, with a median of 46,100 mg/L.

Some water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use

standards were limited. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (all three samples exceeded the SMCL of 500 mg/L), chloride (all three samples exceeded the SMCL of 250 mg/L), and sulfate (all three samples exceeded the SMCL of 250 mg/L).
The produced-water samples generally had concentrations of several properties and constituents that exceeded agricultural-use standards: TDS (all three samples exceeded the WDEQ Class II standard of 2,000 mg/L), chloride (all three samples exceeded the WDEQ Class II standard of 100 mg/L), and sulfate (all three samples exceeded the WDEQ Class II standard of 200 mg/L). The produced-water samples had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (all three samples exceeded the WDEQ Class III standard of 5,000 mg/L), chloride (all three samples exceeded the WDEQ Class III standard of 2,000 mg/L), and sulfate (two of three samples exceeded the WDEQ Class III standard of 3,000 mg/L). All TDS concentrations in the produced-water samples exceeded the State of Wyoming Class IV standard of 10,000 mg/L.

7.3.19 Woodside confining unit

The physical and chemical characteristics of the Woodside confining unit in the Bear River Basin are described in this section of the report.

Physical characteristics

The Woodside confining unit is composed of the Lower Triassic Woodside Shale (**Pl. 5**). The Woodside Shale consists of interbedded red siltstone and shale with minor sandstone and gray limestone interbeds; thickness decreases eastward across the Overthrust Belt from about 390 ft in Idaho to about 650 ft in Wyoming (Kummel, 1954; Lines and Glass, 1975, Sheet 1; Oriel and Platt, 1980; M'Gonigle and Dover, 1992). The Woodside Formation overlies the Dinwoody Formation and is overlain by the Thaynes Limestone in the Bear River Basin (**Pl. 5**). The upper part of the Woodside Shale is stratigraphically equivalent to the Red Peak

Member of the Chugwater Group or Formation (Kummel, 1954).

Little information is available describing the hydrogeologic characteristics of the Woodside Shale. In the Bear River valley, Robinove and Berry (1963, Plate 1) speculated that the Woodside Shale was likely to yield small quantities of groundwater to wells. Lines and Glass (1975, Sheet 1) noted that rocks in the Woodside Shale were relatively impermeable and in most areas were probably capable of yielding only small quantities of water. Ahern et al. (1981, Figure II-7) classified the formation as a confining unit [aquitard] and that definition is tentatively retained herein (**Pl. 5**). Two measurements of discharge (2 and 10 gal/min) from springs issuing from the Woodside confining unit were inventoried as part of this study (**Pl. 4**).

Chemical characteristics
The chemical composition of groundwater in the Woodside confining unit in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from two springs. Individual constituent concentrations in the environmental water samples are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram R**). The TDS concentration (302 mg/L) indicated that the water was fresh (**Appendix E; Appendix G, Diagram R**). On the basis of the few properties and constituents analyzed for in the environmental water samples, the quality of water from Woodside confining unit in the Bear River Basin was likely suitable for most uses. No concentrations of properties or constituents approached or exceeded applicable USEPA or State of Wyoming domestic, agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Woodside confining unit in the Bear River Basin also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram H**). The TDS concentration (25,000 mg/L) indicated that

the water was very saline.

Chemical analyses for few properties and constituents were available for the one produced-water sample; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. Nonetheless, concentrations of some properties and constituents in the Woodside confining unit in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. None of the constituents analyzed had applicable health-based standards. Concentrations of TDS, chloride, and sulfate exceeded aesthetic standards (USEPA SMCLs of 500 mg/L, 250 mg/L, and 250 mg/L, respectively) for domestic use, as well as standards for agricultural use (WDEQ Class II standards of 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively). Concentrations of TDS and chloride also exceeded livestock-use standards (WDEQ Class III standards of 5,000 mg/L and 2,000 mg/L, respectively). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in the produced-water sample.

7.3.20 Dinwoody aquifer and confining unit

The Dinwoody aquifer and confining unit is composed of the Lower Triassic Dinwoody Formation (**Pl. 5**). The Dinwoody Formation consists of basal, middle, and upper units (Kummel, 1954). The 50- to 175-ft thick basal unit of the Dinwoody Formation consists of light tan to tan, silty limestone and calcareous siltstone. The 25- to 350-ft thick middle unit of the Dinwoody Formation consists of interbedded, gray silty limestone, gray crystalline limestone, and olive-light tan to gray shale beds. The 100- to 300-ft thick upper unit consists of interbedded, tan, calcareous siltstone, gray silty limestone, gray crystalline limestone, and a few shale beds. The basal and middle units thin eastward from the Overthrust Belt to zero thickness in Wyoming. Total formation thickness is 545 ft at Cokeville in Sublette Ridge and 180 ft along Muddy Creek in

Lincoln County, Wyoming (Kummel, 1954).

Permeability in the Dinwoody aquifer and confining unit likely is small on a regional scale, and thus, in most areas the unit is probably capable of yielding only small quantities of water from permeable zones where fractures and secondary permeability is present (Lines and Glass, 1975, Sheet 1; Ahern et al., 1981, Table IV-1). Ahern et al. (1981, Figure II-7, and Table IV-1) classified the Dinwoody Formation as a confining unit [aquitard] with locally productive permeable zones in the Overthrust Belt and the adjacent Green River Basin. The investigators (Ahern et al., 1981, Table IV-1) noted that the most productive parts of the Dinwoody Formation were in areas where fractures were present and in interbedded sandstones in the upper part of the formation. In the Wyoming Water Framework Plan, the Dinwoody Formation was classified as a marginal aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**). Because the unit has low overall permeability, but with distinct zones of higher permeability with potential to yield water to wells, the Dinwoody Formation was classified as both an aquifer and confining unit herein (**Pl. 5**). No data were located describing the physical and chemical characteristics of the hydrogeologic unit in the Bear River Basin.

7.4 Paleozoic hydrogeologic units

Lithostratigraphic units of Permian, Pennsylvanian, Mississippian, Devonian, Silurian, Ordovician, and Cambrian age compose the Paleozoic hydrogeologic units in the Bear River Basin (**Pl. 5**). Paleozoic hydrogeologic units (aquifers and confining units) in the Bear River Basin have a combined thickness averaging about 5,000 ft, with a maximum thickness estimated at 9,800 ft (Clarey, 2011). Thickness of Paleozoic hydrogeologic units in the Bear River Basin generally increases to the west. Compared with aquifers of Cenozoic, Mesozoic and Precambrian age, Paleozoic aquifers are the third most used source of water (Clarey, 2011).

Paleozoic hydrogeologic units underlie Cenozoic and Mesozoic hydrogeologic units in the Bear River Basin, except in areas where structural deformation has uplifted and exposed the Paleozoic units in the mountains and highlands of the Overthrust Belt. Outcrops of Paleozoic hydrogeologic units are limited to small areas located along the Crawford thrust fault system in the western part of the Bear River Basin, along the Tunp thrust fault system east of Cokeville, and along the northeastern part of the Bear River Basin (**Pl. 1**). Paleozoic hydrogeologic units are accessible in or very close to these outcrop areas. Paleozoic aquifers produce water from bedrock composed primarily of carbonate rocks [for example, limestone (rock composed of the mineral calcite) and dolostone (rock composed of the mineral dolomite)] and siliciclastic rocks (for example, sandstone) deposited primarily in marine environments. Development of secondary permeability in Paleozoic hydrogeologic units such as fractures, faults, and solution openings is usually required for successful siting and construction of high yielding wells.

Paleozoic hydrogeologic units generally are exposed in the mountains and highlands of the Bear River Basin. The highly complex structural features of the Overthrust Belt require site-specific geologic and hydrogeologic investigation to characterize and develop groundwater resources from Mesozoic and Paleozoic hydrogeologic units. Where structurally deformed by folding and faulting in the Overthrust Belt, permeability of the sandstone, limestone, and dolostone (dolomite) beds composing the Paleozoic hydrogeologic units may be enhanced by bedding-plane partings, faults, fractures, and solution openings.

Like the Mesozoic hydrogeologic units, numerous petroleum (oil and gas) wells are completed in many of the lithostratigraphic units composing the Paleozoic hydrogeologic units, but relatively few water wells are completed in the units, with most in outcrop areas where drilling depths are relatively shallow and waters are relatively fresh. Most of these wells are completed for domestic or stock purposes, but some are used for other purposes. Much of the geologic and hydrogeologic data for the Paleozoic hydrogeologic units are from petroleum exploration. Groundwater in many of the hydrogeologic units, especially away

from outcrop areas and at great depths, is highly mineralized and not suitable for most uses, as indicated by produced-water samples.

7.4.1 Phosphoria aquifer

The physical and chemical characteristics of the Phosphoria aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics
The Phosphoria aquifer is composed of the Permian Phosphoria Formation (**Pl. 5**). The Phosphoria Formation consists of an upper part of dark to light gray, cherty shale and sandstone, and a lower part of brown-weathering, dark, phosphatic shale and limestone. Thickness of the Phosphoria Formation decreases eastward from about 425 ft in Idaho to about 230 ft in Wyoming (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992).

The formation is divided into two members at some locations. The Rex Chert Member is composed of dark gray siltstone, black, thin-bedded chert and limestone, and a few thin beds of phosphate rock in the upper part. Resistant ledges of gray, cherty, dolomitic limestone and some bedded chert are present in the middle and lower part of the Rex Chert Member (Rubey et al., 1980). The Meade Peak Member consists of dark gray, non-resistant, and brown phosphatic siltstone and cherty siltstone, gray dolomite, several blue beds of phosphorite, and one bed of vanadium-bearing carbonaceous siltstone (Rubey et al., 1980). Individual members are not shown on **Plate 5**.

The Phosphoria Formation is classified as an aquifer by most investigators and that definition is retained herein (**Pl. 5**). Robinove and Berry (1963, p. V18) identified the Phosphoria Formation and the underlying Wells Formation as potential Paleozoic aquifers in the Bear River valley; the investigators noted that both formations "may be expected to yield small to moderate amounts of water to wells." Primary permeability in the Phosphoria aquifer likely is small, and in most areas the unit probably is capable of yielding only "small quantities" of water (Lines and Glass, 1975, Sheet

1). However, in areas where fractures are present and secondary permeability is developed, the aquifer is capable of yielding "moderate quantities" of water (Lines and Glass, 1975, Sheet 1). Ahern et al. (1981, Figure II-7, and Table IV-1) classified the Phosphoria Formation as a locally confining minor aquifer in the Overthrust Belt and adjacent Green River Basin (**Pl. 5**). The investigators (Ahern et al., 1981, Table IV-1) noted that the most productive parts of the Phosphoria Formation were in areas where fractures were present and in interbedded sandstones in the upper part of the formation. In the Wyoming Water Framework Plan, the Phosphoria Formation was classified as a minor aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**).

Hydrogeologic data describing the Phosphoria aquifer, including spring-discharge and well-yield measurements and other hydraulic properties, are summarized on **Plate 4**. One discharge (300 gal/min) was inventoried for a spring issuing from the Phosphoria aquifer (**Pl. 4**). One well-yield measurement for a flowing well (200 gal/min) was inventoried as part of this study and indicates that the Phosphoria aquifer is capable of providing moderate quantities of water at some locations in the Bear River Basin (**Pl. 4**). Two estimates of transmissivity for the Phosphoria aquifer (0.17 and 0.46 ft²/d) were inventoried (**Pl. 4**).

Chemical characteristics
The chemical composition of groundwater in the Phosphoria aquifer in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations in the environmental water sample are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram S**). The TDS concentration from the spring (1,230 mg/L) indicated that the water was slightly saline, and the TDS concentration from the well (4,560 mg/L) indicated that the water was moderately saline (**Appendix E; Appendix G, Diagram S**).

Concentrations of some properties and constituents in water from the Phosphoria aquifer in the Bear

River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. Most environmental waters were suitable for domestic use, as no concentrations of constituents exceeded health-based standards (USEPA MCLs and HALs). Concentrations of several properties and constituents exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (well and spring samples exceeded the SMCL of 500 mg/L), sulfate (well and spring samples exceeded the SMCL of 250 mg/L), chloride (well sample exceeded the SMCL of 250 mg/L), and fluoride (well sample exceeded the SMCL of 2 mg/L).

Concentrations of some properties and constituents exceeded State of Wyoming standards for agricultural and livestock use in the Bear River Basin. Properties and constituents in environmental water samples that had concentrations greater than agricultural-use standards were sulfate (well and spring samples exceeded the WDEQ Class II standard of 200 mg/L), TDS (well sample exceeded the WDEQ Class II standard of 2,000 mg/L), and chloride (well sample exceeded the WDEQ Class II standard of 100 mg/L). No concentrations of properties or constituents approached or exceeded applicable State of Wyoming livestock water-quality standards.

7.4.2 Wells aquifer

The physical and chemical characteristics of the Wells aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics
The Wells aquifer is composed of the Lower Permian and Upper to Middle Pennsylvanian Wells Formation (**Pl. 5**). The Wells Formation consists of interbedded gray limestone and pale yellow calcareous sandstone with minor gray dolomite beds; the lower part of the formation is cherty. Thickness of the Wells Formation decreases eastward from about 2,000 ft in Idaho to about 600 ft in Wyoming (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992).

The Wells Formation is classified as an aquifer by most investigators and that definition is retained herein (**Pl. 5**). In the Cokeville area, Berry (1955) identified the Wells Formation (referred to as the Tensleep Sandstone) as a potential aquifer (**Pl. 5**). Robinove and Berry (1963, p. V18) identified the Wells Formation and overlying Phosphoria Formation as potential Paleozoic aquifers in the Bear River valley; the investigators noted that both formations "may be expected to yield small to moderate amounts of water to wells." Similarly, Lines and Glass (1975, Sheet 1) noted that sandstone beds composing the formation were aquifers capable of yielding moderate to large quantities of water, depending upon local recharge, sandstone bed continuity, and development of secondary permeability from fractures. In addition, the investigators (Lines and Glass, 1975, Sheet 1) noted that sandstone beds "on topographic highs may be drained, especially if underlying limestones have extensive solution development." Ahern et al. (1981, Figure II-7, and Table IV-1) classified the Wells Formation as a major aquifer in the Overthrust Belt and adjacent Green River Basin (**Pl. 5**). In the Wyoming Water Framework Plan, the Wells Formation was classified as a major aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**).

Hydrogeologic data describing the Wells aquifer, including spring-discharge and well-yield measurements and other hydraulic properties, are summarized on **Plate 4**. One discharge (1,800 gal/min) was inventoried for a spring issuing from the Wells aquifer (**Pl. 4**). Two measurements of yields from wells completed in the Wells aquifer (300 and 700 gal/min) were inventoried (**Pl. 4**). One specific capacity for one well completed in the Wells aquifer was inventoried and was 6 (gal/min)/ft (**Pl. 4**). One estimate of transmissivity for one well completed in the Wells aquifer was inventoried and was 1,340 ft²/d (**Pl. 4**). Porosity estimates obtained from petroleum exploration ranged from 2 to 12 percent (**Pl. 4**). One permeability estimate obtained from petroleum exploration was inventoried and was 0.2 millidarcy (**Pl. 4**).

Chemical characteristics
The chemical composition of groundwater in

the Wells aquifer in the Bear River Basin was characterized and the quality evaluated on the basis of environmental water samples from one well and one spring. Individual constituent concentrations in the environmental water sample are listed in **Appendix E**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix G, Diagram T**). The TDS concentration from the spring (110 mg/L) and the well (521 mg/L) indicated that the waters were fresh (**Appendix E; Appendix G, Diagram T**). On the basis of the few properties and constituents analyzed for in the environmental water samples, the quality of water from the Wells aquifer in the Bear River Basin was likely suitable for most uses. Environmental waters from both samples were suitable for domestic use, as no concentrations of constituents exceeded health-based standards (USEPA MCLs and HALs). Concentrations of one property (TDS) exceeded aesthetic standards (USEPA SMCLs) for domestic use (well sample exceeded the SMCL of 500 mg/L). No concentrations of properties or constituents approached or exceeded applicable State of Wyoming agriculture, or livestock water-quality standards.

The chemical composition of groundwater in the Wells aquifer in the Bear River Basin also was characterized and the quality evaluated on the basis of one produced-water sample from one well. Individual constituent concentrations for this sample are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram I**). The very large TDS concentration (144,000 mg/L) indicated that the water was briny and, combined with other very poor water-quality characteristics, was unlikely to be usable for any purposes. Chemical analyses for few properties and constituents were available for the one produced-water sample; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. Nonetheless, concentrations of some properties and constituents in the Wells aquifer in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for

some uses. None of the constituents analyzed had applicable health-based standards. Concentrations of TDS, chloride, and sulfate exceeded aesthetic standards (USEPA SMCLs of 500 mg/L, 250 mg/L, and 250 mg/L, respectively) for domestic use, as well as standards for agricultural use (WDEQ Class II standards of 2,000 mg/L, 100 mg/L, and 200 mg/L, respectively). Concentrations of TDS and chloride also exceeded livestock-use standards (WDEQ Class III standards of 5,000 mg/L and 2,000 mg/L, respectively). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in the produced-water sample.

7.4.3 Amsden aquifer

The Amsden aquifer is composed of the Upper Mississippian to Pennsylvanian Amsden Formation (**Pl. 5**). The Amsden Formation consists of red and gray cherty limestone and yellow siltstone, sandstone, and conglomerate; formation thickness decreases eastward across the Overthrust Belt from about 560 ft in Idaho to about 150 ft in Wyoming (Mallory, 1967; Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992). The Amsden Formation is overlain by the Wells Formation and underlain by the Madison Limestone (**Pl. 5**). The Amsden Formation has been divided into as many as three members in some areas, including the Ranchester Limestone Member (Lower Pennsylvanian), the Horseshoe Shale Member (Upper Mississippian to Lower Pennsylvanian), and the Darwin Sandstone Member (Upper Mississippian) (Mallory, 1967).

Little information is available describing the hydrogeologic characteristics of the Amsden Formation in the Bear River Basin, so much of what is known about the hydrogeologic characteristics of the formation is from the Green River Basin to the east and adjacent areas. Lines and Glass (1975, Sheet 1) noted that small quantities of water might be available from cherty limestone in the formation in the Overthrust Belt, but "on topographic highs, the Amsden Formation is probably well-drained, especially if underlying limestones have extensive solution development." Ahern et al. (1981, Figure II-7, and Table IV-1) classified the formation as a minor locally confining

aquifer in the Overthrust Belt and adjacent Green River Basin (**Pl. 5**). In the Wyoming Water Framework Plan, the Amsden Formation was classified as a marginal aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**). Previous studies of the Amsden Formation in the adjacent Green River Basin and surrounding areas have classified the formation as an aquifer (Ahern et al., 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein); classification of the formation as an aquifer was retained herein (**Pl. 5**). In the upper Colorado River Basin and adjacent areas, Geldon (2003) classified the Ranchester Limestone and the Darwin Sandstone Members as aquifers and the Horseshoe Shale Member as a confining unit (see Bartos and Hallberg, 2010, Figure 5-4). Few hydrogeologic data describing the characteristics of the Amsden aquifer in the Bear River Basin were inventoried as part of this study. One transmissivity estimate of 0.05 ft²/ day related to petroleum exploration was inventoried (**Pl. 4**). No data were located describing the chemical characteristics of the Amsden aquifer in the Bear River Basin.

7.4.4 Madison aquifer

The physical and chemical characteristics of the Madison aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics
The Madison aquifer is composed of the Lower to Upper Mississippian Madison Limestone (**Pl. 5**). The Madison Limestone consists of an upper part of light gray, massive limestone and a lower part of dark gray, thin-bedded limestone; dolostone (carbonate rock composed of the mineral dolomite) also is present throughout the formation (Lines and Glass 1975; Oriel and Platt, 1980). Thickness of the Madison Limestone ranges from about 1,000 ft to more than 1,800 ft in the Overthrust Belt (Lines and Glass 1975; Oriel and Platt, 1980).

Little information is available describing the hydrogeologic characteristics of the Madison Limestone in the Bear River Basin, so much of what is known about the hydrogeologic characteristics of the formation is from the Green

River Basin to the east and adjacent areas. Ahern et al. (1981, Figure II-7, and Table IV-1) classified the formation as a major aquifer in the Overthrust Belt and adjacent Green River Basin (**Pl. 5**). In the Wyoming Water Framework Plan, the Madison Limestone was classified as a major aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**). Previous studies of the Madison Limestone in the adjacent Green River Basin and surrounding areas have classified the formation as an important regional aquifer (Ahern et al., 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein); classification of the formation as an aquifer in the Bear River Basin was retained herein (**Pl. 5**).

Like other Paleozoic carbonate aquifers in the Bear River Basin (Bighorn, Darby and Gallatin aquifers), permeability in the Madison aquifer is primarily in areas where secondary permeability is developed, primarily from fractures, bedding-plane partings, and solution openings (Ahern et al., 1981, Figure II-7, and Table IV-1; Geldon, 2003). Lines and Glass (1975, Sheet 1) noted that Madison Limestone outcrops have ancient solution openings (paleokarst) that probably developed before and during deposition of the overlying Amsden Formation, and thus, secondary permeability due to solution openings in the Madison aquifer probably is present at great depths below the land surface. In areas without secondary permeability development, primary permeability of the Madison Limestone is very small to nonexistent (impermeable) and the unit can be considered a confining unit.

Few hydrogeologic data describing the characteristics of the Madison aquifer in the Bear River Basin were inventoried as part of this study. Porosity estimates obtained from petroleum exploration ranged from 2 to 20 percent (**Pl. 4**). Permeability estimates obtained from petroleum exploration ranged from 0.23 to 1.5 millidarcies (**Pl. 4**).

Chemical characteristics
The chemical composition of groundwater in the Madison aquifer also was characterized and the quality evaluated on the basis of eight produced-water samples from wells. Summary statistics

calculated for available constituents are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram J**). TDS concentrations were variable and indicated that most waters were briny (50 percent of samples) and remaining waters were fresh to very saline (**Appendix F; Appendix H, Diagram J**). TDS concentrations ranged from 327 to 160,000 mg/L, with a median of 29,700 mg/L.

The available water-quality analyses were from produced-water samples, for which chemical analyses of few properties and constituents were available; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. None of the constituents analyzed had applicable health-based standards. The produced-water samples generally had concentrations of several properties and constituents that exceeded aesthetic standards (USEPA SMCLs) for domestic use: TDS (seven of eight samples exceeded the SMCL of 500 mg/L), chloride (seven of sight samples exceeded the SMCL of 250 mg/L), sulfate (five of eight samples exceeded the SMCL of 250 mg/L), and pH (one of eight samples below lower SMCL limit of 6.5and one of eight samples above upper SMCL limit of 8.5).

The produced-water samples generally had concentrations of several properties and constituents that frequently exceeded agricultural-use standards: TDS (seven of eight samples exceeded the WDEQ Class II standard of 2,000 mg/L), chloride (seven of eight samples exceeded the WDEQ Class II standard of 100 mg/L), and sulfate (five of eight samples exceeded the WDEQ Class II standard of 200 mg/L). The produced-water samples generally had concentrations of several properties and constituents that exceeded livestock-use standards: TDS (seven of eight samples exceeded the WDEQ Class III standard of 5,000 mg/L), chloride (seven of eight samples exceeded the WDEQ Class III standard of 2,000 mg/L), pH (one of eight samples below lower WDEQ Class III limit of 6.5 and one of eight samples above upper WDEQ Class III limit of 8.5), and sulfate (one of eight samples exceeded the

WDEQ Class III standard of 3,000 mg/L). Class IV standard of 10,000 mg/L for TDS was exceeded in six of eight produced-water samples.

7.4.5 Darby aquifer

The Darby aquifer is composed of the Upper Devonian Darby Formation (**Pl. 5**). The Darby Formation consists of an upper part of black, yellow, and red sandstone and siltstone and a lower part of dark gray dolomite and dolomitic limestone; thickness of the formation ranges from about 450 to 885 ft (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992).

Little information is available describing the hydrogeologic characteristics of the Darby Formation in the Bear River Basin, so much of what is known about the hydrogeologic characteristics of the formation is from the Green River Basin to the east and adjacent areas. Ahern et al. (1981, Figure II-7, and Table IV-1) classified the formation as a major aquifer in the Overthrust Belt and adjacent Green River Basin (**Pl. 5**). In the Wyoming Water Framework Plan, the Darby Formation was classified as a major aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**). Previous studies of the Darby Formation in the adjacent Green River Basin and surrounding areas have classified the formation as an important regional aquifer (Ahern et al., 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein); classification of the formation as an aquifer in the Bear River Basin was retained herein (**Pl. 5**).

Like other Paleozoic carbonate aquifers in the Bear River Basin (Madison, Bighorn, and Gallatin aquifers), permeability in the Darby aquifer is primarily in areas where secondary permeability is developed, primarily from fractures, bedding-plane partings, and solution openings (Ahern et al., 1981, Figure II-7, and Table IV-1; Geldon, 2003). In areas without secondary permeability development, primary permeability of the Darby Formation is very small to nonexistent (impermeable) and the unit can be considered a confining unit.

Few hydrogeologic data describing the characteristics of the Darby aquifer in the Bear River Basin were inventoried as part of this study. Two porosity estimates obtained from petroleum exploration were 2 and 7 percent (**Pl. 4**). No data were located describing the chemical characteristics of the hydrogeologic unit.

7.4.6 Laketown Dolomite

The Silurian Laketown Dolomite (**Pl. 5**) is composed of medium to light gray, white-weathering, fine-crystalline, thick-bedded dolomite; formation thickness decreases eastward from about 1,300 ft in Idaho to about 1,000 ft in Wyoming (Oriel and Platt, 1980). The Laketown Dolomite is present only in the southwestern corner of Lincoln County and is absent elsewhere in Wyoming, either due to non-deposition or later erosion that removed most Silurian lithostratigraphic units in Wyoming. No data were located describing the physical and chemical characteristics of the lithostratigraphic unit.

7.4.7 Bighorn aquifer

The physical and chemical characteristics of the Bighorn aquifer in the Bear River Basin are described in this section of the report.

Physical characteristics
The Bighorn aquifer is composed of the Upper Ordovician Bighorn Dolomite (**Pl. 5**). The Bighorn Dolomite consists primarily of light gray massive dolomite and dolomitic limestone, and thickness decreases eastward from about 820 ft in Idaho to about 400 ft in Wyoming (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980; Ahern et al., 1981; M'Gonigle and Dover, 1992).

Little information is available describing the hydrogeologic characteristics of the Bighorn Dolomite in the Bear River Basin, so much of what is known about the hydrogeologic characteristics of the formation is from the Green River Basin to the east and adjacent areas. Ahern et al. (1981, Figure II-7, and Table IV-1) classified the formation as a major aquifer in the Overthrust Belt and adjacent Green River Basin (**Pl. 5**). In the Wyoming Water

Framework Plan, the Bighorn Dolomite was classified as a major aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**). Previous studies of the Bighorn Dolomite in the adjacent Green River Basin and surrounding areas have classified the formation as an aquifer (Ahern et al., 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein); classification of the formation as an aquifer in the Bear River Basin was retained herein (**Pl. 5**).

Like other Paleozoic carbonate aquifers in the Bear River Basin (Madison, Darby, and Gallatin aquifers), permeability in the Bighorn aquifer is primarily in areas where secondary permeability is developed, primarily from fractures, bedding-plane partings, and solution openings (Ahern et al., 1981, Figure II-7, and Table IV-1; Geldon, 2003). In areas without secondary permeability development, primary permeability of the Bighorn Dolomite is very small to nonexistent (impermeable) and the unit can be considered a confining unit.

Little quantitative hydrogeologic information is available describing the physical or chemical characteristics of the Bighorn aquifer in the Bear River Basin because few wells are completed in the aquifer, but available hydraulic properties are summarized in **Plate 4**. Porosity estimates obtained from petroleum exploration ranged from 2 to 8 percent (**Pl. 4**). Permeability estimates obtained from petroleum exploration ranged from 0.1 to 0.75 millidarcies (**Pl. 4**).

Chemical characteristics
The chemical composition of groundwater in the Bighorn aquifer in the Bear River Basin also was characterized and the quality evaluated on the basis of two produced-water samples from two wells. Individual constituent concentrations for these samples are listed in **Appendix F**. Major-ion composition in relation to TDS is shown on a trilinear diagram (**Appendix H, Diagram K**). The TDS concentrations (14,500 and 19,000 mg/L) indicated that the waters were very saline.

Chemical analyses for few properties and constituents were available for the two produced-

water samples; thus, comparisons between concentrations in produced-water samples and health-based, aesthetic, or State of Wyoming agricultural and livestock-use standards were limited. Nonetheless, concentrations of some properties and constituents in the Bighorn aquifer in the Bear River Basin approached or exceeded applicable USEPA or State of Wyoming water-quality standards and could limit suitability for some uses. None of the available constituents analyzed for had applicable health-based standards. Concentrations of TDS (SMCL of 500 mg/L and WDEQ Class III standard of 5,000 mg/L) and chloride (SMCL of 250 mg/L and WDEQ Class III standard of 2,000 mg/L) in both samples, and pH (above upper SMCL and WDEQ Class III limit of 8.5) in one sample exceeded aesthetic standards (USEPA SMCLs) for domestic use and State of Wyoming standards for livestock use. Concentrations of TDS and chloride also exceeded agricultural-use standards (WDEQ Class II standards of 2,000 mg/L and 100 mg/L, respectively). The WDEQ Class IV standard of 10,000 mg/L for TDS was exceeded in both produced-water samples.

7.4.8 Gallatin aquifer

The Gallatin aquifer is composed of the Upper Cambrian Gallatin Limestone (**Pl. 5**). The Gallatin Limestone consists of interbedded, mottled yellow and tan, thin-bedded to massive dolostone (carbonate mineral composed of the mineral dolomite) and limestone; thickness ranges from 230 to 400 ft (Lines and Glass 1975; Oriel and Platt, 1980; Rubey et al., 1980; M'Gonigle and Dover, 1992).

Little information is available describing the hydrogeologic characteristics of the Gallatin Limestone in the Bear River Basin, so much of what is known about the hydrogeologic characteristics of the formation is from the Green River Basin to the east and adjacent areas. Ahern et al. (1981, Figure II-7, and Table IV-1) classified the formation as a minor aquifer in the Overthrust Belt and adjacent Green River Basin (**Pl. 5**). In the Wyoming Water Framework Plan, the Bighorn Dolomite was classified as a minor aquifer (WWC

Engineering et al., 2007, Figure 4-9) (**Pl. 5**). Previous studies of the Gallatin Limestone in the adjacent Green River Basin and surrounding areas have classified the formation as an aquifer (Ahern et al., 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein); classification of the formation as an aquifer in the Bear River Basin was tentatively retained herein (**Pl. 5**).

Like other Paleozoic carbonate aquifers in the Bear River Basin (Madison, Darby, and Bighorn aquifers), permeability in the Gallatin aquifer is primarily in areas where secondary permeability is developed, primarily from fractures, bedding-plane partings, and solution openings (Ahern et al., 1981, Figure II-7, and Table IV-1; Geldon, 2003). In areas without secondary permeability development, primary permeability of the Gallatin Limestone is very small to nonexistent (impermeable) and the unit can be considered a confining unit. No data were located describing the physical and chemical characteristics of the hydrogeologic unit in the Bear River Basin.

7.4.9 Gros Ventre confining unit

The Gros Ventre confining unit is composed of the Middle to Upper Cambrian Gros Ventre Formation (**Pl. 5**). The Gros Ventre Formation is composed of gray and tan, oolitic in part, limestone with green-gray micaceous shale in the middle of the formation; thickness of the formation decreases eastward from about 1,300 ft in Idaho to about 650 ft in Wyoming (Lines and Glass 1975; Oriel and Platt, 1980).

Little information is available describing the hydrogeologic characteristics of the Gros Ventre Formation in the Bear River Basin, so much of what is known about the hydrogeologic characteristics of the formation is from the Green River Basin to the east and adjacent areas. Ahern et al. (1981, Figure II-7, and Table IV-1) classified the formation as a confining unit [aquitard] or regional confining unit [regional aquitard] in the adjacent Green River Basin and in the Overthrust Belt (**Pl. 5**). In the Wyoming Water Framework Plan, the Bighorn Dolomite was classified as a minor aquifer (WWC Engineering et al., 2007, Figure

4-9) (**Pl. 5**). Previous studies of the Gros Ventre Formation in the adjacent Green River Basin and surrounding areas have classified the formation as a confining unit (Ahern et al., 1981; Geldon, 2003; Bartos and Hallberg, 2010, and references therein); classification of the formation as a confining unit in the Bear River Basin was tentatively retained herein (**Pl. 5**). No data were located describing the physical and chemical characteristics of the hydrogeologic unit.

7.4.10 Flathead aquifer

The Flathead aquifer is composed of the Lower Cambrian Flathead Sandstone (**Pl. 5**). The Flathead aquifer is confined from above by the Gros Ventre confining unit and from below by the Precambrian basal confining unit (**Pl. 5**). The Lower Cambrian Flathead Sandstone in the Overthrust Belt is composed of white to pink, fine-grained sandstone and some lenses of coarse-grained sandstone; the upper part of the formation includes some green silty shale interbeds, and the lower part is conglomeratic (Lines and Glass, 1975). Thickness of the quartzitic Flathead Sandstone ranges from about 175 to 200 ft in the northern Overthrust Belt (Schroeder, 1969).

Little information is available describing the hydrogeologic characteristics of the Flathead Sandstone in the Bear River Basin, so much of what is known about the hydrogeologic characteristics of the formation is from the Green River Basin to the east and adjacent areas and elsewhere in Wyoming. Ahern et al. (1981, Figure II-7, and Table IV-1) classified the formation as a minor aquifer in the Overthrust Belt and adjacent Green River Basin (**Pl. 5**). In the Wyoming Water Framework Plan, the Flathead Sandstone was classified as a major aquifer (WWC Engineering et al., 2007, Figure 4-9) (**Pl. 5**). Previous studies of the Flathead Sandstone in the adjacent Green River Basin and surrounding areas have classified the formation as an aquifer (Ahern et al., 1981; Taylor et al., 1986; Lindner-Lunsford et al., 1989; Geldon, 2003; Bartos and Hallberg, 2010, and references therein); classification of the formation as an aquifer in the Bear River Basin was tentatively retained herein (**Pl. 5**). Based on lithology, Lines

and Glass (1975, Sheet 1) noted that the Flathead Sandstone in the Overthrust Belt was "probably a potential source of water." No data were located describing the physical and chemical characteristics of the hydrogeologic unit in the Bear River Basin.

Reported descriptions of Flathead aquifer permeability in Wyoming varies by investigator and the location examined. In the Wind River Basin and Granite Mountains area, Richter (1981, Table IV-1) reported that porosity and permeability is intergranular, but that secondary permeability is present along bedding-plane partings and as fractures associated with folds and faults; the investigator classified the Flathead Sandstone as a "major aquifer" in the Wind River Basin and adjacent Granite Mountains area. Similarly, in the Bighorn Basin, previous investigators (Cooley, 1984, 1986; Doremus, 1986; Jarvis, 1986; Spencer, 1986) also reported intergranular porosity and permeability but also noted secondary permeability development along bedding-plane partings and as fractures associated with folds; all of these investigators classified the Flathead Sandstone as an aquifer. In contrast, Boner et al. (1976) and Weston Engineering, Inc. (2008) noted that the Flathead Sandstone in the southern Powder River Basin and northern flank of the Laramie Mountains was well cemented and poorly sorted with little primary (intergranular) permeability. In addition, Weston Engineering (2008, p. II-4) also noted that bedding-plane partings may provide some permeability, but that silica cement in the formation is not readily dissolved, and that "permeability of the unit is likely to be similar to that of the underlying Precambrian rocks."

7.5 Precambrian basal confining unit

The Precambrian basal confining unit consists of undifferentiated nonporous igneous and metamorphic rocks of the Precambrian basement that act as a basal confining unit for the Flathead aquifer, as well as for all aquifers and aquifer systems in the Bear River Basin (**Pl. 5**). The Precambrian rocks are composed mainly of quartzite with minor quantities of schist and gneiss. The Precambrian basal confining unit is not exposed at land surface within the Bear

River Basin, but underlies the younger geologic formations at greater depths. Precambrian rocks are exposed at land surface in areas adjacent to the Bear River Basin in southeastern Idaho and northern Utah and in the adjacent Snake-Salt and Green River Basins of Wyoming. Compared with hydrogeologic units of Cenozoic, Mesozoic, and Paleozoic age, the Precambrian basal confining unit is the least used and in fact, does not appear to be used as a source of water for any purposes in the Bear River Basin (Clarey, 2011). No data were located describing the physical and chemical characteristics of the hydrogeologic unit in the Bear River Basin.

Chapter 8

Groundwater Development and Basin-wide Water Balance

Karl Taboga, James Stafford and Paul Taucher

Several factors to consider when planning a groundwater development project include:

- Is the resource economically accessible utilizing current drilling, well construction, and water delivery technology?
- Is the water quality sufficient to meet the requirements of its intended use in either an untreated form or following cost effective treatment?
- Is the resource legally available? Legal and political considerations such as competing local water rights, aquifer and surface water depletion, and wildlife impacts constrain groundwater availability under the developing concept of sustainability.
- Can the aquifer provide sufficient quantities of water? Quantity pertains to the rate and duration of production that can be reasonably expected from the completed project wells.

Project engineers, scientists, water managers, operations personnel, and end users continuously evaluate these interrelated factors during a project because a substantial deficiency in any one area may render the entire project infeasible.

Groundwater development in the Bear River Basin is further constrained by the Amended Bear River Compact of 1978 (**Appendix D**) between the states of Utah, Wyoming, and Idaho. The compact limits and defines water appropriations from the Bear River for all three states. To effectively discuss groundwater development and use within a river basin, the term "withdrawal" and the concept of "consumptive use" must be defined and discussed. A groundwater withdrawal is simply the removal of a volume of water from a well or a spring at its source. The consumptive use of a water resource diminishes the amount of water available for other uses and effectively removes that water as a useable resource from the drainage basin. Consumptive processes include evaporation, transpiration, and injection into geologic units where depth and water quality preclude future withdrawal.

Relatively few uses are wholly consumptive. Most uses are partially consumptive in that some of the water is lost while the remainder is returned to the system until it flows out of the basin. For instance, a portion of the groundwater used for irrigation is lost to the consumptive processes of evapotranspiration while the remainder is delivered back to the basin's water budget as return flows to surface waters or as recharge to groundwater. Other examples of consumptive uses include livestock watering, surface water evaporation and municipal, industrial and domestic. Some wastewater treatment depletions include discharge in sewage or septic systems where water is depleted through evaporation and transpiration. Industrial depletions can be in the form of evaporative cooling, wastewater storage and disposal in evaporation pits and water injection for enhanced oil and gas production. Throughout this study "use" has essentially the same meaning as "withdrawal," and "depletion" has the same meaning as "consumptive use." The preferred terms, in an attempt to minimize confusion, are "withdrawal" and "consumptive use."

This chapter discusses groundwater development, total withdrawals, and depletions in the Bear River Basin using information compiled from multiple sources:

- Previous water plans for the Bear River Basin (WWC Engineering and others, 2007; Forsgren Associates 2001;Wyoming Water Development Office (WWDO), 2012);
- Numerous previous local and regional studies (**Appendix B, Chapter 7**);
- Groundwater permit data provided by the Wyoming State Engineer's Office (SEO), the Idaho Department of Water Resources (IDWR), and the Utah Division of Water Rights (UDWR); and
- SEO 2012 Hydrographers' Annual Report Water Division 4 (State Engineer's Office, 2013) available at: https://sites.google.com/a/wyo.gov/seo/interstate-streams/know-your-basin/bear-river-basin.

8.1 Information from previous water plans

Total groundwater withdrawals, consumptive uses, and the methods used to quantify them in the Bear River Basin were described in the existing WWDC Statewide Framework Water Plan (WWC Engineering and others, 2007), which compiled and updated information from the 2001 Bear River Basin Water Plan (Forsgren and Associates, 2001), associated technical memoranda, and other on-line publications. Although the 2007 Statewide Water Plan summarized withdrawal and consumptive use information developed in the 2001 Bear River Basin Plan, there were small differences in the volumes reported between the two plans and the various technical memoranda. Direct measurements of irrigation uses were not provided in the WWDC Water Plans but were estimated based on related information. Estimates of consumptive uses associated with recreational and environmental uses of groundwater resources were not provided in the previous plans or technical memoranda.

8.2 Groundwater withdrawal and consumptive use estimations and basin-wide water balance

In the absence of direct measurements, ground-water withdrawals and consumptive uses must be estimated. While this may appear to be straightforward, in reality, it becomes quite complex because multiple estimations of the same parameter may be made using different methods and assumptions. Still, the methods used must provide reasonably conservative estimations of withdrawals and consumptive uses based on rational assumptions. Therefore, withdrawal and consumptive use values are presented, in the tables shown below, in multiple formats and as ranges of probable values. In some cases, very conservative estimations have been provided for comparison and are explained in the text that accompanies the table. See, for example, the range of annual irrigation withdrawal estimates from SEO data made in rows 2 - 3 of **Table 8-1a**.

The water resources of any river basin are not composed of static volumes of standing water. Unlike an area's mineral reserves, water is a dynamic

resource that enters a basin in the form of precipitation or as surface and groundwater flows from adjacent areas. Likewise, water exits a river basin as effluent surface and groundwater flows or as water vapor resulting from evaporation, and transpiration from plants (see definition, **Chapter 5**). It is important to understand the transient nature of water resources. For this reason, the Wyoming State Geological Survey (WSGS) generated a basin-wide water balance (**Tables 8-2a** and **8-2b**) to provide an understanding of the magnitude, origin and fate of water resources in the Bear River Basin.

8.2.1 Groundwater withdrawal and consumptive use estimations

Tables 8-1a through **8-1d** summarize and compare various groundwater withdrawal and consumptive use estimates from the SEO and previous WWDC water plans and technical memoranda (WWC Engineering and others, 2007; Forsgren and Associates, 2001; WWDO 2012) for principal SEO listed water right uses.

- Irrigation (**Table 8–1a**);
- Stock watering (**Table 8–1a**);
- Industrial uses (**Table 8–1b**);
- Community and non-community public supply (**Table 8–1c**);
- Rural domestic (**Table 8–1c**); and
- Other diverse uses (**Table 8–1d**) that involve miscellaneous, monitoring, test, multi-use wells, and are hereinafter, referred to as "minor uses."

Although the values developed for **Tables 8-1a** through **8-1e** and **Tables 8-2a** through **8-2d** are shown in some cases to a precision of 1 ac-ft., they are generally rounded to the nearest 100 ac-ft. in the following discussion. Percentages carried to one decimal place in the tables are rounded to the nearest whole value.

Estimates of total withdrawal and consumptive use volumes for the first five uses listed above are shown in **Tables 8-1a** through **8-1c** and are aggregated in **Table 8-1e**. Total annual groundwater withdrawal is 3,900 ac-ft and the corresponding value for annual consumptive use is 3,130 ac-ft

Table 8-1a. Groundwater withdrawal and consumptive use estimates for agricultural use wells (irrigation and stock watering) in the Wyoming portion of the Bear River Basin.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive-use (ac-ft/yr)	Percent consumptive use	Estimation method/ Data sources/ Notes
[1] SEO permitted irrigation wells	58,762	no estimate		SEO permitted yields for irrigation wells through 02/27/12. (See Table 8-6)
	11,605	no estimate		SEO permitted yields for likely existing irrigation wells through 02/27/12. (See Table 8-6)
[1] SEO permitted livestock wells	5,667	no estimate		Total permitted yield through 02/27/12. (See Table 8-6)
	4,214	no estimate		Permitted yield for likely existing stock wells through 02/27/12. (See Table 8-6)
[2,3] Agricultural uses	2,400	1,900	80 - 100%	Irrigation and livestock use estimates are aggregated as agricultural uses. Mean annual crop consumptive use of groundwater for 1971 - 1998 in Bear River Basin is 80% of withdrawals. Stock use considered 100% consumptive.

Table 8-1b. Groundwater withdrawal and consumptive use estimates for industrial use wells in the Wyoming portion of the Bear River Basin.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive-use (ac-ft/yr)	Percent consumptive use	Estimation method / Notes
[1] Permitted industrial wells	2,847	no estimate		Total permitted yield through 02/27/12. (See Table 8-6)
	0	no estimate		Total permitted yield for likely existing wells through 02/27/12. (See Table 8-6)
[2] Industrial uses (primarily for gas processing)	5	5	100.0%	All industrial uses were assumed to be 100% consumptive
[3] WOGCC Conventional Oil & Gas produced water (2005-2011)	466	222	47.6%	An estimated 47.6% of produced water was re-injected

(**Table 8-1e**). Water use categories, amounts, and estimation methods are discussed in more detail later in this chapter. Minor uses are not included in the totals shown in **Table 8-1e**, because they are not addressed in previous water plans and only SEO permitted withdrawal data (**Table 8-1d**) is available for them.

For other uses, potential volumes calculated from SEO allocated well yields are provided for comparison to estimates obtained from previous technical memoranda. The large differences between SEO allocated well yields and actual use estimates show that the volumes of groundwater actually used constitute a fraction of what has been allocated to permitted water right holders. For example, the total irrigation withdrawal calculated from SEO permitted yields for "likely existing wells" (11,605 ac-feet/yr in **Table 8-1a**) assumes continuous year-round operation of the permitted irrigation wells. Although, the value is clearly an overestimate, it does provide an instructive upper limit of groundwater withdrawals for irrigation. The estimates shown for agricultural withdrawals and consumptive uses of groundwater are aggregate values for both irrigation and stock watering (Forsgren and Associates, 2001; WWDO 2012). Irrigation consumptive uses were based on actual crop specific consumptive uses in the Bear River Basin collected over a 28-year period of record from 1971-1998. The methodology is explained in **Appendix G** of the 2001 Bear River Basin Water Plan (Forsgren and Associates, 2001).

Table 8-1a: Estimates of total groundwater withdrawals and consumptive uses for irrigation and stock watering (combined as agricultural uses) obtained from various sources. Values from **Appendix G** (Forsgren and Associates, 2001) shown in **Table 8-1a** are used in **Table 8-1**e.

Table 8-1b: Estimates for various classes of industrial groundwater withdrawals and consumptive uses, shown in **Table 8-1b**, are compiled from SEO and WOGCC data and the previous 2011 Bear River Basin Water Plan (WWDO 2012). Note that the volumes of saline water produced from oil and gas operations are not generated as a groundwater resource, but only as a byproduct. These values therefore are not considered a reduction of beneficially useable groundwater resources but were provided for the reader's information.

Table 8-1c: Estimates for municipal and domestic groundwater withdrawals and consumptive uses are shown in **Table 8-1c**. The ranges of consumptive uses, shown and aggregated with other uses in **Table 8-1e**, are compiled from previous water plans and technical memoranda (Forsgren and Associates, 2001; WWDO 2012).

Table 8-1c. Groundwater withdrawal and consumptive use estimates for municipal and domestic use wells in the Wyoming portion of the Bear River Basin.

Use	Annual withdrawal (ac-ft/yr)	Annual consumptive-use (ac-ft/yr)	Percent consumptive use	Estimation method / Notes
[1] Permitted municipal and domestic wells	17,550	no estimate		Total permitted yield through 02/27/12. (Table 8-6)
	8,530	no estimate		Permitted yield for likely existing wells through 02/27/12.(Table 8-6)
[2] Municipal / Community GW	801	692	86%	Groundwater withdrawals/use for Towns of Cokeville/Bear River
[2] Rural domestic	533	533	100%	Rural domestic use assumed to be 100% consumptive.
[2] TOTAL	1,334	1,225	91.8%	Combined municipal and rural domestic use

Table 8-1d. Permitted annual groundwater withdrawal rates for SEO monitor, multi-use and other wells in the Wyoming portion of the Bear River Basin.

Use	Annual withdraw-al (ac-ft/yr)	Annual consump-tive-use (ac-ft/yr)	Percent consump-tive use	Estimation method / Notes
[1] Permitted municipal and domestic wells	17,550	no estimate		Total permitted yield through 02/27/12. (Table 8-6)
	8,530	no estimate		Permitted yield for likely existing wells through 02/27/12.(Table 8-6)
[2] Municipal / Community GW	801	692	86%	Groundwater withdrawals/use for Towns of Cokeville/Bear River
[2] Rural domestic	533	533	100%	Rural domestic use assumed to be 100% consumptive.
[2] TOTAL	1,334	1,225	91.8%	Combined municipal and rural domestic use
[1] Wyoming State Engineer's Office, 2012 [2] Wyoming Water Development Office, 2012				

Table 8-1e. Total groundwater withdrawal and consumptive use estimates for all uses in the Bear River Basin.

Use	Annual withdrawal (ac-ft/yr)	Annual Consump-tive-Use (ac-ft/yr)	Percent Con-sumptive Use	Estimation method / Notes
Total permitted yield Wyoming	[1] 128,631	no estimate		Total permitted yield through 02/27/12 (See Table 8-6)
	[1] 36,987	no estimate		Permitted yield for likely existing wells through 02/27/12 (See Table 8-6)
Total permitted yield Wyoming, Utah, Idaho	[1,2,3] 295,163	no estimate		1,362 WSEO permits as of 02/27/12 1 IDWR permits as of 09/20/12 981 UDWR permits as of 09/20/12 (See Tables 8-6, 8-7, 8-8)
Estimated withdrawals and consumptive uses from Wyoming agricultural , municipal, domestic and industrial wells [4,5]	3,900	3,130	80.3%	Totals estimated in 2011 Bear River Basin Water Plan[4]
	3,739	3,130	83.7%	Totals of estimates from Tables 8-1a, 8-1b and 8-1c
[1]Wyoming State Engineer's Office (2012) [2]Idaho Department of Water Resources (2012) [3]Utah Division of Water Rights (2012) [4]Forsgren and Associates 2001 [5]Wyoming Water Development Office, 2012				

Table 8-1d: Only SEO permitted withdrawal information was available for several minor uses - monitor, other, and multi-use wells.

Table 8-1e: Total groundwater withdrawal and consumptive use estimates are shown for principal SEO listed uses, all Utah Division of Water Rights (UDWR) and Idaho Department of Water Resources (IDWR) uses, aggregated values from **Tables 8-1a** through **8-1c**, and totals compiled from the 2011 Bear River Basin Water Plan and associated technical memoranda.

8.3 Basin-wide water balance

Tables 8-2a and **8-2b** contain mass balance water budget calculations for the Wyoming portion of the Bear River Basin. The primary objective of the water balance analysis is to provide a rational estimate of basin-wide evapotranspiration. In the process, withdrawal, consumptive use, and recharge data from this and other chapters in this report are conveniently compiled into one table. Armed with these estimates, first order approximations can be made of the proportions of precipitation destined for recharge, evapotranspiration, surface water outflows and consumptive uses from water resource development.

The analysis contained in **Table 8-2a** was adapted from the general water budget equation (Fetter, 2001):
Evapotranspiration = (precipitation + surface inflow + imported water + groundwater inflow) – (surface water outflow + groundwater outflow + reservoir evaporation + exported water + recharge) ± changes in surface water storage ± changes in groundwater storage.

- The assumptions used in this water balance are:
- No water is imported or exported into or from the Bear River Basin.
- Basin groundwater inflows equal basin groundwater outflows.
- Groundwater and surface water depletions are limited to consumptive uses from the municipal/domestic, livestock, and industrial sectors (SEO permitted uses).

- Annual changes in stored surface and groundwater equal zero.

8.3.1 Precipitation

Precipitation is the ultimate source of groundwater recharge. Average annual precipitation volume in the Bear River Basin for the 30-year period of record (POR) from 1981 to 2010 was calculated using GIS software and PRISM data (http://prism. oregonstate.edu/ - Figure 3-3) at 1,398,195 ac-ft.

8.3.2 Surface water inflows and outflows

Average annual stream inflow and outflow data for the Wyoming portion of the basin were obtained from the USGS (http://water.usgs.gov/). Inflow data was retrieved from USGS stream gaging stations 10011500, 10012500, 10015700 and 10026500, all of which are sited near the Utah-Wyoming border on influent reaches of the Bear River and tributary streams.

Annual outflow data was recovered from USGS stream gaging stations 10020500, 10027000, 10039500, and 10041000. These stations are all sited on effluent reaches of the Bear River and tributary streams near Wyoming's borders with Utah and Idaho.

8.3.3 Evaporation from reservoirs

Evaporation data from the basin's reservoirs was obtained from Technical Memorandum XI of the 2011 Bear River Basin Water Plan (WWDO, 2012).

8.3.4 Depletions from municipal/domestic, livestock, and industrial uses)

Surface water and groundwater depletions from municipal/domestic, livestock, and industrial uses were obtained from the 2011 Bear River Basin Water Plan (WWDO, 2012). Agricultural uses were not considered since 99.9 percent of irrigation water is lost to evapotranspiration and return flows that recharge underlying aquifers or discharge

Table 8-2a. Bear River Basin water resources mass balance.

WATER BALANCE PARAMETERS[a]		Average Annual Volume (ac-ft)
Precipitation (1981 - 2010 - Figure 3-3)[b]		1,398,195
Total surface water inflows[c]	+	340,337
Total surface water outflows[c]	-	503,592
Evaporation from reservoirs[d]:	-	5,361
Water exported (Surface water depletions from municipal/domestic, livestock, and industrial uses)[d]	-	2,676
Water exported (Groundwater depletions from municipal/domestic, livestock, and industrial uses)[d]	-	1,574
Total estimated Bear River Basin recharge (Table 6-3)	-	188,968
Basin-wide evapotranspiration	=	1,036,361

Comparative estimates

The Wyoming Climate Atlas[e] indicates that, except for the highest elevations in Wyoming, the <u>rate</u> of evaporation exceeds the <u>rate</u> of precipitation by at least a factor of 4. The potential evaporation <u>rate</u> can greatly exceed the actual volume.

For comparison - total average annual precipitation: 1,398,195 x 4 =	5,592,780 acre-feet
Estimation evapotranspiration in the Bear River Basin using the USGS climate and land-cover data regression[f] .	
Total evapotranspiration	1,069,066 acre-feet

[a]Fetter, C. W., 2001
[b]PRISM Climate Group, 2012
[c]USGS, 2012
[d]Wyoming Water Development Office, 2012
[e]Curtis, 2004
[f]Sanford and Selnick, 2013

to surface water bodies (Colorado State University, 2013).

8.3.5 Total estimated Bear River Basin recharge

The recharge value shown is the "best total recharge" estimate for sedimentary aquifers calculated on **Tables 6-2** and **6-3** from the recharge fraction data of Hamerlinck and Arneson (1998) and PRISM (2013) precipitation data for the 1981 – 2010 POR.

8.3.6 Estimated basin-wide evapotranspiration

The water balance model adapted from Fetter (2001) and presented in **Table 8-2a** places basin-wide evapotranspiration at 1,036,361 acre –feet per year. For comparison, a value for potential evapotranspiration (5,592,780 acre-feet per year) was provided based on the premise that the rate of evapotranspiration exceeds the rate of precipitation by a factor of at least four (Curtis, 2004). Potential evapotranspiration is the amount of water that would evaporate and transpire if there is always a sufficient amount of water available in the soil

to meet demand (Sharp, 2007). In fact, actual evapotranspiration is limited to the amount of water available to the processes of evaporation and transpiration.

A second estimate of actual evapotranspiration (1,069,066 acre-feet per year) in the Bear River Basin is shown at the bottom of Table 8-2a. This estimate was obtained using a GIS based regression model developed by the USGS (Sanford and Selnick, 2013) from climate and land-cover data. The USGS ET estimate falls within 3.2% (32,705 acre-feet) of the estimate obtained using the water balance method.

8.4 Magnitude, origin and fate of water resources in the Bear River Basin

Table 8-2b shows that approximately 74 percent of precipitation is lost to evapotranspiration in the Bear River Basin, about 14 percent recharges the basin's aquifers and nearly 12 percent leaves as stream outflow. Evaporation from reservoirs constitutes less than 0.4 percent of total basin precipitation. Surface water and groundwater depletions from municipal/domestic, livestock, and industrial

uses comprise 0.2 percent and 0.1 percent of precipitation, respectively.

Table 8-2c summarizes various average groundwater withdrawal estimates from tables 8-1a through 8-1c as percentages of estimated recharge. Agricultural (irrigation and livestock) and aggregated municipal and domestic uses each constitute about 1 percent, industrial uses amount to less than 0.01 percent, and total groundwater withdrawals constitute about 2 percent of recharge. Estimated total annual consumptive uses (3,739 acre-feet - Table 8-1e) constitute about 2 percent of annual average recharge.

Estimated recharge (**Table 8-2c**) far exceeds average annual withdrawals of groundwater. Estimates of total average annual groundwater use could be substantially higher, and the estimates of recharge substantially lower, without significantly changing these simple comparative results.

Table 8-2d: It is also useful to evaluate future groundwater requirements relative to recharge. The 2001 Bear River Basin Water Plan (Forsgren and Associates, 2001) provides use factor-based estimates of total combined annual withdrawals and

Table 8-2b. Bear River Basin water balance parameters as percent of precipitation.[b]

WATER BALANCE PARAMETERS[a]	% of Precipitation
Net stream outflows[c]	11.68%
Evaporation from reservoirs[d]:	0.38%
Water exported (Surface water depletions from municipal/domestic, livestock, and industrial uses)[d]	0.19%
Water exported (Groundwater depletions from municipal/domestic, livestock, and industrial uses)[d]	0.11%
Total estimated Bear River Basin recharge (Table 6-3)	13.52%
Basin-wide evapotranspiration	74.12%
Total	100.00%

[a]Fetter, C. W., 2001

[b]PRISM Climate Group, 2012

[c]USGS, 2012

[d]Wyoming Water Development Office, 2012

Table 8-2c. Summary of groundwater use statistics as percentage of recharge in the Wyoming portion of the Bear River Basin.

Groundwater-use statistics	Annual volume (acre-feet)	Percentage of calculated recharge
[1]Total estimated recharge (acre-feet)	188,968	-----
[3]Average annual groundwater withdrawals		
[2] Agricutural uses (irrigation and stock watering)	2,400	1.3%
[2]Municipal & domestic	1,334	0.7%
[2]Industrial	5	0.003%
[2]TOTAL	3,739	2.0%

consumptive uses for agricultural, municipal, rural domestic and industrial uses in 2030. The analysis examines normal and maximum water demand cases for low and high economic growth scenarios. Projected future annual groundwater requirements for the 30-year timeframe are determined as percentages of annual recharge estimated in **Chapter 6**.

Overall groundwater demands projected for 2030 range from 3 percent of recharge for low growth / normal demand, to 6 percent for high growth / high demand conditions. So it appears that estimated recharge volumes are adequate to meet not only current withdrawals (**Table 8-2c**) but future groundwater demands, as well. However, these analyses do not consider legal constraints imposed by the Amended Bear River Compact that may limit future groundwater development. The potential for overutilization of groundwater resources is

location-specific, both hydrologically and legally, and must be evaluated during the planning stage of any development project. Evaluating potential groundwater resources of the Bear River Basin outside of existing environmental regulations and legal restrictions is beyond the scope of this study.

8.5 Groundwater withdrawals by use

The following sections discuss the uses that account for nearly all estimated groundwater withdrawals in the 2001 and 2011 Bear River Basin Water Plans (Forsgren and Associates, 2001; WWDO 2012) and the 2007 Statewide Framework Water Plan (WWC Engineering and others, 2007). Tables 8-6 through 8-8 show the number of groundwater permits by use for the portions of Wyoming, Utah, and Idaho, respectively, that fall within the boundaries of the Bear River Basin examined in this

Table 8-2d. Summary of future groundwater requirements as percentages of recharge

Economic scenario	Low growth			High growth		
[1]Water demand scenario	Normal demand		High demand	Normal demand		High demand
Groundwater demand - 2030 total withdrawals (acre-feet)	6,518	-	8,860	7,963	-	10,675
Percentage of estimated recharge	3.4%	-	4.7%	4.2%	-	5.6%
Groundwater demand - 2030 consumptive use (acre-feet)	2,646	-	3,433	3,580	-	4,535

report (**Figure 3-1**). The "other" category includes miscellaneous wells.

8.5.1 Irrigation

Direct measurements of groundwater volumes used for irrigation are not presented in either the 2001 or 2011 Bear River Basin final report (Forsgren and Associates 2001; WWDO 2012) or in the 2007 State Framework Water Plan (WWC Engineering and others, 2007). Instead, estimates of irrigation uses for combined surface water and groundwater based on water use factors were developed using crop-specific information from 1971 through 1998. From these, total diversions and consumptive uses were generated for four cases formulated from low and high economic growth scenarios within the context of both normal and maximum water demand conditions determined for the year 2001(Forsgren and Associates, 2001). The same procedure was used to predict total irrigation diversions and consumptive uses for the year 2030. The 2001 study estimated the proportions of groundwater and surface water that constitute total withdrawals and consumptive use for all evaluated uses. Groundwater withdrawals and consumptive volumes were then back-calculated for all uses; see **Tables 8-1a** and **8-2d** (Forsgren and Associates, 2001).

In the Bear River Basin, most irrigation wells are located along the river and its tributaries where water is obtained from the relatively shallow Bear River Alluvium. Irrigation uses are partially consumptive due to crop ET; consumptive uses are estimated at 80 percent of total withdrawals for irrigation (Forsgren and Associates, 2001; WWDO 2012). Within the Bear River Basin, 43 SEO and 47 Utah Division of Water Resources (UDWR) permits have been issued solely for irrigation use. Updated data for total permits and permitted yields from the SEO, UDWR, and IDWR is shown in **Tables 8-6** through **8-8** and in **Figure 8-1**.

8.5.2 Livestock watering

Withdrawals and consumptive uses for livestock watering were estimated in the 2001 Water Plan (Forsgren and Associates, 2001) at 528 ac-ft/

yr (**Table 8-2c**) using stock-specific daily water requirements of 12 gal/day/animal for cattle and 2 gal/day/animal for sheep. It was assumed that all of the water used for livestock watering is consumptively used surface water. The 2011 Water Plan estimated that livestock consumptive use was 350 ac-ft per year drawn from both surface and groundwater sources but did not assign a use value specific to groundwater (WWDO 2012). Irrigation and livestock groundwater consumptive uses, aggregated in the summary section of both reports as agricultural uses, were listed at 1,900 ac-ft per year. In the Bear River Basin, 215 SEO permits and 115 UDWR permits have been issued solely for stock watering (**Tables 8-6, 8-7,** and **8-8**).

8.5.3 Municipal/community public water systems

Municipal/community public water systems supply water year-round to essentially the same population (http://www2.epa.gov/region8-waterops). **Chapter 5** of the 2011 Water Plan (WWDO 2012) contains groundwater use information for community public water systems from the Water System Survey Report (WWDO 2009), the EPA Public Water System database (http://www2.epa.gov/region8-waterops), and directly from water system operators and administrators. For systems that otherwise lacked information, average and peak use volumes were calculated by multiplying per capita values obtained from well documented systems (Evanston, Cokeville, and Bear River) by the population served. Average annual municipal use of groundwater in the Bear River Basin is summarized by communities that obtain all or part (conjunctive use of surface and groundwater sources) of their supply from groundwater in Section 5.3 and Tables 5-8 through 5-17 of the 2011 Bear River Basin Water Plan (WWDO 2012). Community (municipal) groundwater total withdrawals noted in Table 5-16 of the 2011 plan are summarized in **Table 8-1c** of this report. Consumptive use of combined community and domestic groundwater withdrawals is reported in the 2011Bear River Basin Water Plan (WWDO 2012) at 80 percent of the above total withdrawal estimates.

Municipal/community use constitutes a relatively small part of overall groundwater consumptive uses in the Bear River Basin (**Table 8-2a**). As of February 27, 2012, the SEO issued 8 permits for exclusive municipal use in the Bear River Basin (**Table 8-6**). In addition to the municipal use permits, many of the wells that supply water to the basin's municipalities and communities (**Tables 8-9** through **8-11**) are permitted as multiple use or miscellaneous wells.

8.5.4 Rural domestic use

Rural domestic withdrawals are defined as household uses that are not supplied by municipal water systems. Nearly all rural domestic supplies are drawn from groundwater. Rural domestic use was determined by calculating rural population size (municipal population subtracted from basin population, (Wyoming Economic Analysis Division, 2008) and then multiplying by an average per capita withdrawal rate of 180 gallons per day (WWDO 2012). The per capita use rates were obtained from the 2001 Bear River Basin Water Plan (Forsgren and Associates, 2001). Average rural domestic water usage was estimated at 533 ae-ft/yr (**Table 8-1c**). The consumptive use rate was assumed to be 100 percent of domestic groundwater withdrawals.

Rural domestic use constitutes a small part of overall groundwater withdrawals in the Bear River Basin (**Table 8-2a**). Actual rural domestic withdrawals are much less than the amounts projected from SEO permitted yields because domestic wells are typically used intermittently while SEO projections assume continuous use. In addition, it is likely that some of the permits are inactive. The mapped distribution of domestic permits in the Bear River Basin (**Figure 8-4**) indicates that most rural domestic wells are completed in the Bear River alluvium. Domestic wells are also completed in basin's principle bedrock aquifers, while a smaller number are completed in confining units. **Tables 8-6** through **8-8** indicate that, in the Bear River Basin, 418 domestic wells permits have been issued in Wyoming, 416 in Utah and one in Idaho (the only Idaho permit listed for any use in that portion of the Bear River Basin considered in this study).

8.5.5 Combined municipal and domestic withdrawals and consumptive use

Table 6-4 in the 2011 Water Plan (WWDO 2012) contains projections of municipal and rural domestic groundwater uses as part of an economic study of future groundwater demands for the Bear River Basin (**Table 8-2d**). The study projected that combined Wyoming annual municipal and domestic consumptive uses of surface water and groundwater would reach 2,703 and 1,326 acre-feet, respectively by 2030. According to these projections, consumptive uses would increase by only 8 – 9 percent over 2009 levels. Total municipal and rural domestic withdrawals from groundwater were estimated at about 25 percent of total diversions. Based on the difference between municipal diversions and effluent discharge, consumptive use of surface water and groundwater was estimated at approximately 59 and 92 percent of withdrawals, respectively. The higher rate of consumptive use for groundwater is due, in part, to the assumption that all water withdrawn from rural domestic wells is used consumptively.

8.5.6 Recreational and environmental uses

Although water in Wyoming has been developed primarily to provide supplies for irrigation, flood control, and for hydroelectric power generation, recreational uses must also be considered. The majority of recreational water use is associated with surface water bodies (swimming, fishing, camping, hunting, and boating) and snow (skiing and snowmobiling); although these activities are non-consumptive, they do rely on adequate and consistent water sources. Only a few recreational uses, such as snowmaking and turf irrigation, are consumptive. The Bear River Basin 2011 Water Plan (WWDO, 2012) did not estimate how much groundwater is used for recreation, but noted that growing recreational uses are important in the Bear River Basin and should be considered during future project planning.

The Bear River Basin 2011 Water Plan (WWDO 2012) discusses environmental water uses such as

maintaining minimum stream flows and reservoir water levels to protect wildlife habitat and fisheries. Specifically, these include surface water withdrawals required to meet SEO in-stream flow filings, U.S. Forest Service instream bypasses, and voluntary minimum levels for US Bureau of Reclamation reservoirs designed to produce and protect fisheries habitat that historically have been impacted by low flow conditions. Consumption of water for environmental uses is minimal and due primarily to evaporative loss. Except for groundwater discharges to surface waters, which are undetermined, environmental uses of groundwater are not addressed.

8.5.7 Industrial uses (WWDO, 2012)

The 2011 Bear River Basin Water Plan (WWDO 2012) identified the most important industrial water users and estimated current groundwater withdrawals by industrial facilities (**Table 8-1b**). Industrial applications use minimal amounts of groundwater in the Bear River Basin (**Table 8-2c**). Chevron and BP Amoco are the primary industrial consumers of groundwater in the Bear River Basin. Industrial consumptive uses of water, primarily for gas processing, are limited to about 47 acre-feet per year, of which 5 acre-feet consist of groundwater. The remainder is drawn from surface water sources (WWDO 2012).

To quantify industrial water use, the authors of the 2011 Bear River Basin Water Plan (WWDO 2012) evaluated SEO permit information for industrial and miscellaneous uses, and conducted follow up interviews and written surveys of permit holders. The 2011 Water Plan (WWDO 2012) provides details on industrial groundwater use within the Bear River Basin. An examination of updated records on the SEO database for this study found that as of February 27, 2012, 11 groundwater permits for industrial operations had been issued in the Bear River Basin (**Table 8-6**).

Chapter 6 of the 2011 Bear River Basin Water Plan predicted that industrial uses of groundwater may increase to 15 acre-feet per year by 2030 under a high economic growth scenario. Otherwise, under a low growth scenario, industrial groundwater use is expected to drop to zero by 2030.

Discharges of groundwater withdrawn as a byproduct during conventional oil and gas production are not required to be permitted with SEO and were estimated from WOGCC information compiled for this study. Records of produced water injection were also obtained from the WOGCC (Table 8-1b). An average of 466 ac-ft of groundwater was generated annually from 2003 through 2012 during oil and gas production, and an average of 222 ac-ft/yr of produced water was injected over the same time. In contrast to groundwater withdrawn during conventional oil and gas production, groundwater produced during coal bed natural gas (CBNG) operations is regulated by the SEO and WDEQ. No SEO permits for CBNG wells have been issued for the Bear River Basin and WOGCC records confirm that there are no current groundwater withdrawals for CBNG in the Bear River Basin.

Groundwater withdrawn for industrial, fuels, and non-fuels mining applications may be of naturally poor quality and in some cases industrial processes degrade water quality. Most industrial groundwater that is not initially used consumptively is either discharged to the surface (sometimes after treatment) under a Wyoming Pollution Discharge Elimination System WYPDES permit issued by WDEQ, injected for permanent disposal, or reused for enhanced oil and gas production. Some industrial wastewater, including water coproduced with oil and gas, is evaporated at permitted disposal reservoirs. In some cases industrial wastewater is reused for general industrial purposes such as dust control. Because produced water from oil and gas operations is a byproduct, it probably would not be withdrawn for any other purpose. Injecting produced water for enhanced oil and gas recovery or permanent disposal into aquifers generally too deep to be considered for groundwater development effectively removes water from the system and is, therefore, consumptive.

Produced water withdrawal and injection volumes were not included on either side of the water balance equation in this report but were provided on

Table 8-1b for the reader's information. A review of industrial discharges under the authority of WYPDES permits indicates that there are three industrial WYPDES permits: one for the Painter Natural Gas Plant now owned by Merit Energy and two permits for travel centers (restaurants and refueling stations for travelers and the trucking industry). The wastewater from the natural gas plant is discharged to a sedimentation pond and then ultimately re-injected. One WYPDES permit for the Kemmerer Mine, owned by Chevron Mining, lists one outfall which discharges to the Bear River Basin; the other seven outfalls discharge to the Green River Basin. The discharges are composed of treated pit water and storm runoff from disturbed areas. Discharges from these permits are small and were not considered in the water balance presented in this chapter.

8.6 Information from hydrogeologic unit studies

In addition to the withdrawal and consumptive use data compiled from previous state water plans, aquifer-specific groundwater use information was compiled from a variety sources for the discussion in **Chapter 7** of hydrogeologic units in the Bear River Basin. **Chapter 7** summarizes the physical, hydrogeologic, and chemical characteristics of the principal hydrogeologic units in the Bear River Basin including the known dynamics of recharge, discharge, and groundwater circulation.

Appendix B provides a chronological summary of the locations, aquifers, focus, results, and status of groundwater development studies that have been sponsored by the WWDC since 1973 in the Bear River Basin. Many of these studies were used to compile the information presented in **Chapter 7**.

8.7 Groundwater permit information

Groundwater development proceeds primarily by installing water supply wells and, to a lesser degree, by developing natural springs. Permits allowing the appropriation of groundwater are issued and administered by the SEO in Wyoming, the Department of Water Resources (IDWR) in Idaho, and the Division of Water Rights (UDWR) in Utah.

For this study, the WSGS acquired groundwater permit data from all three agencies. The SEO provided information for 1,362 groundwater permits through February 27, 2012, including 315 newer permits issued after December 31, 2000 (**Tables 8-3** and **8-6**). UDWR provided data for 981 Utah groundwater permits through September 20, 2012. Data was obtained on one Idaho groundwater permit from the IDWR through September 20, 2012 in the Idaho part of the Bear River Basin (**Table 8-8**). Limitations and other characteristics of the groundwater-permits databases are described in **Appendix C**. Information for specific SEO groundwater permits can be accessed through the SEO online water rights database at: http://seo.state.wy.us/wrdb/PS_WellLocation.aspx. The database is easy to use and specific information can be queried using various search parameters (e.g., permit number, location, applicant, use).

Groundwater permit information from the UDWR can be accessed at: http://maps.waterrights.utah.gov/mapserver/scripts/search.asp

Information on specific groundwater permits from the IDWR can be accessed at: http://www.idwr.idaho.gov/WaterManagement/default.htm Permits to appropriate groundwater in the Bear River Basin have been mapped for this study and certain data has been tabulated in formats that are highly informative. The maps of permit locations by use contained in **Chapter 8** illustrate the spatial distribution of particular types of groundwater wells throughout the Bear River Basin. Groundwater permit data is tabulated in this section to summarize the number of permits by:

1. SEO permit status, depth range, and yield range;
2. Class of use (SEO, UDWR, IDWR);
3. SEO municipal use, including producing hydrogeologic unit;
4. WDEQ Source Water Assessment Program (SWAP).

In addition, permit data are tabulated on maps depicting locations of likely drilled wells (**Figures 8-1** through **8-6**). SEO data are tabulated and mapped in this study for all permits through February 2012

Table 8-3. SEO groundwater permits in the Bear River Basin listed by permit status.

Permit Status	All Permits through 2000	New Permits since 2001
Fully Adjudicated	50	6
Complete	850	139
Unadjudicated	0	5
Incomplete	60	79
Undefined	87	86
Total Permits	*1,047*	*315*
Probable Wells Drilled	*900 - 987*	*150 - 236*
	(86- 91%)	*(48 - 75%)*

and for permits from 2001 through February 2012 to illustrate development over the last decade.

8.7.1 Groundwater permits by permit status

Table 8-3 shows the number of groundwater permits issued by the SEO under eight permit-status categories. **Table 8-3** does not include permits from either the UDWR or the IDWR. In Wyoming, the status categories are:

1. *Fully Adjudicated* – the well has been drilled and inspected, and a certificate of appropriation issued.
2. *Complete* – SEO has received a notice of completion of the well.
3. *Unadjudicated* – the well has not yet been inspected but may have been drilled.
4. *Incomplete* – SEO has not received a notice of completion of the well.
5. *Undefined* – a permit without a designated status. These include the following discontinued status categories:
   - *Abandoned* – SEO has received a notice that the well has been physically abandoned.
6. *Expired* – the permit to appropriate groundwater has expired, generally because SEO has not received a notice that the well has been completed within the time period specified in the original permit or extension(s).

7. *Cancelled* – the permit has been cancelled, generally by the original permit applicant.

The SEO issues permits granting water rights to applicants. This does not necessarily mean that a well has been completed and in most cases, it is not known with any certainty whether a well was installed in association with a specific permit. To estimate the number of wells that have likely been completed for each use, the Wyoming State Geological Survey (WSGS) assumed that wells probably have been completed for fully adjudicated, complete, abandoned and unadjudicated permits. In contrast, wells are likely not completed in association with incomplete and undefined permits. **Table 8-3** summarizes the number of likely drilled wells for each use in the Bear River Basin. Based on these assumptions, at least 86 percent of wells permitted through 2000 are likely to have been installed (i.e., completed) compared to at least 48 percent of wells permitted since 2001.

8.7.2 Groundwater permits by depth and yield

Table 8-4 shows the number of permits by depth range and **Table 8-5** shows the number of permits by yield range. **Tables 8-4** and **8-5** do not include permits from the UDWR or the IDWR.

Approximately 99 percent of all SEO groundwater permits for which depth data are available are for wells less than 500 feet deep, and approximately 92 percent are for wells less than 100 feet deep.

Table 8-4. SEO groundwater permits in the Bear River Basin listed by depth range.

Depth Range(feet)	All Permits		Cumulative	
	Permits	Percentage	Permits	Percentage
1-50	800	79.37%	800	79.37%
51-100	125	12.40%	925	91.77%
101-500	73	7.24%	998	99.01%
501-1000	6	0.60%	1004	99.60%
> 1000	4	0.40%	1008	100.00%
Total Permits with Depth information	1008	--	--	--
Permits with no Depth information	354	25.99%	1362	--
Total Permits	1362	(of Total)	--	--
Depth Range(feet)	New Permits since 2001		Cumulative	
	Permits	Percentage	Permits	Percentage
1-50	117	80.69%	117	80.69%
51-100	18	12.41%	135	93.10%
101-500	10	6.90%	145	100.00%
501-1000	0	0.00%	145	100.00%
> 1000	0	0.00%	145	100.00%

All SEO groundwater permits issued from 2001 through February 2012, were for wells less than 500 feet deep, and approximately 93 percent were for wells less than 100 feet deep. In the SEO database, many of the permits (54 percent issued after 2001 and 26 percent overall) do not include well depth.

Of the 1,185 groundwater permits in the Bear River Basin database for which yield information is available, approximately 90 percent are permitted for yields of 0-25 gpm both for permits issued after 2001 and for total permits. Less than three percent of permits issued after 2001 and less than 2 percent of total permits are for yields greater than 1,000 gpm. Approximately seven percent of both types of permits (issued after 2001 and total permits) have been issued for yields greater than 100 gpm. Many of the permits (13 percent issued after 2001 and 17 percent overall) in the SEO database do not include permitted yield.

Permitted depths and yields, and the mapped permit locations on **Figures 8-1** through **8-6** illustrate that most wells in the Bear River Basin are planned and completed in near-surface, Quaternary hydrogeologic units.

8.7.3 Groundwater permits by use: tables, figures, and matrix tables

Groundwater permit information, by use, is presented in **Tables 8-6** through **8-8** and **Figures 8-1** through **8-6**, and the matrix tables contained in the figures. This information was obtained from the SEO, the UDWR, and the IDWR. All of these agencies issue permits granting water rights to applicants. In many cases, especially with older permits, it is not known with any certainty whether a well or spring improvement was actually installed in association with a specific permit. Furthermore, existing facilities might have been abandoned after some time and are no longer being used beneficial-

Table 8-5. SEO groundwater permits in the Bear River Basin listed by yield range.

Yield Range(gpm)	All Permits		Cumulative	
	Permits	Percentage	Permits	Percentage
1-25	1070	90.30%	1070	90.30%
26-100	38	3.21%	1108	93.50%
101-500	36	3.04%	1144	96.54%
501-1000	22	1.86%	1166	98.40%
> 1000	19	1.60%	1185	100.00%
Total Permits with Yield information	1185	--	--	--
Permits with no Yield information	177	13.00%	1362	--
Total Permits	1362	(of Total)	--	--
Yield Range(gpm)	New Permits since 2001		Cumulative	
	Permits	Percentage	Permits	Percentage
1-25	235	89.69%	235	89.69%
26-100	9	3.44%	244	93.13%
101-500	5	1.91%	249	95.04%
501-1000	7	2.67%	256	97.71%
> 1000	6	2.29%	262	100.00%
Total Permits with Yield information	262	--	--	--
Permits with no Yield information	53	16.83%	315	--
Total Permits	315	(of Total)	--	--

ly. Any examination of permitted uses must explain how the permit data was processed and what it actually represents. The permit data presented in the following two sections differs between the figures and the tables:

- **Tables 8-6, 8-7,** and **8-9** show the number of groundwater permits issued in Wyoming, Utah, and Idaho, respectively, by permitted use regardless of permit status (**Section 8.4.1**). This means that all permits issued are listed without evaluating if a well was installed. The tables list six single primary use categories (municipal, domestic, industrial, irrigation, stock, and monitoring), an "other" category for all other single uses, and a "multi-use" category for permits that list more than one use. (Approximately 30 percent of all groundwater permits in the Bear River Basin are for multiple uses). The "other"

category includes permits issued for "miscellaneous uses," and minor uses such as test wells. The number of permits given for a single use (e.g., eight total permits for municipal use in **Table 8-6**) includes neither "multi-use" permits which may allow municipal use in addition to other uses nor those permits listed as "other" which may allow municipal withdrawals. Additionally, values for "total permitted yield" calculated by summation of all permits with listed yields and "total likely yield" determined by analysis of permit status are provided.

- **Figures 8-1** through **8-6** show the number of "likely drilled wells", determined by analysis of permit status (**Section 8.4.1**) for each of the six primary use categories (municipal, domestic, industrial, irrigation, stock, and monitoring). This includes permits where one use is listed. For example, the number of municipal wells is

determined by counting single use "municipal" wells and any "multi-use" permits which include "municipal" as one of the permitted uses. Thus, multi-use wells are counted several times, once for each listed use.

- Matrix tables contained in each of the figures, present the number of all permits issued for each use combined in all three states (**Figure 3-1**) regardless of permit status. This includes permits where one use is listed, for example "municipal" as well as "multi-use" permits which include "municipal" as one of the permitted uses.

8.7.3.1 Groundwater permits by use: Tables 8-6, through 8-11

Tables 8-6, 8-7, and **8-8** show that most groundwater permits in the Bear River Basin are for domestic use at individual residences, followed by multi-use, and stock wells.
Additionally, total likely yields (permitted yields from wells that are likely to be completed) constitute a fraction of the total permitted yields. A comparison of total likely yields to total permitted yields for each use suggests that a higher proportion of domestic and stock wells were completed and used beneficially than any other type of wells.

Tables 8-9 and **8-10** are expanded summary tables for SEO permits that include municipal uses, and **Table 8-11** summarizes information on SWAP wells and springs that are used for both municipal and non-community public water supply. A brief discussion of the SWAP is provided in **Section 8.4.3.7**. The SWAP provides some information beyond what is available in the SEO groundwater permits data.

8.7.3.2 Groundwater permit location maps and matrix tables, by use

Six maps (**Figures 8-1** through **8-6**) were prepared for this study to illustrate the geospatial distribution of groundwater permits according to use in the Bear River Basin. Only permits for wells that were likely to have been drilled (including abandoned wells) are included on **Figures 8-1** through **8-6**. Groundwater permits are mapped relative to their date of issue (before or after January 1, 2001) on Bear River Basin scale maps and by total well depths on subregion scale figures. Figures have been provided for the following permitted uses:

- Irrigation (**Figure 8-1**)
- Livestock (**Figure 8-2**)
- Municipal (**Figure 8-3**)
- Domestic (**Figure 8-4**)
- Monitoring (**Figure 8-5**)

Table 8-6. SEO groundwater permits in the Bear River Basin listed by intended use.

Well Type	WSEO Code	Total Number of Permits	New Since 2001	Total Permitted Yield (gpm)	Total Likely Yield* (gpm)
Municipal	MUN	8	2	4,150	100
Domestic	DOM	418	107	6,723	5,185
Industrial	IND	11	0	1,764	0
Irrigation	IRR	43	10	36,406	7,190
Stock	STK	215	53	3,511	2,611
Monitor	MON	147	45	1	1
Other	MIS, blank	112	21	4,169	1,189
Multi-Use	various	408	77	22,970	6,639
Total		1,362	315	79,693	22,915

*Includes only wells that are Fully Adjudicated, Complete, and Unadjudicated.

Table 8-7. Utah DWR groundwater permits in the Bear River Basin listed by intended use.

Well Type	Total Number of Permits	New Since 2001	Total Permitted Yield (gpm)
Municipal	11	6	2,265
Domestic	416	126	1,973
Industrial	0	0	0
Irrigation	47	6	35,525
Stock	144	17	2,147
Monitoring	0	0	0
Other	134	4	7,380
Multi-use	229	37	53,880
Total	981	196	103,170

- Miscellaneous-use and other wells (**Figure 8-6**)
- USGS spring locations are shown on **Plate 3**

Industrial permit wells were not mapped because there are relatively few of them (**Table 8-6**), and they withdraw and consume minor amounts of groundwater (**Table 8-1b**).

Figures 8-1 through **8-6** differentiate groundwater permits issued from January 1, 2001 through February 27, 2012 in order to evaluate how groundwater development in the Bear River Basin has proceeded during the past decade. Substantial groundwater development has occurred in the Bear River Basin since the 2001 Groundwater Determination (Forsgren and Associates, 2001). Consistent with the historic trend, it is clear that most permits issued over the 2001 – 2012 period in the Bear

River Basin continue to target Quaternary and Tertiary hydrogeologic units.

Matrix tables that correlate ranges of well depths and yields for all permits issued are also provided on the groundwater permit maps. Consistent with **Tables 8-4** and **8-5**, the depth vs. yield tables shows that by far the most permits issued in the Bear River Basin are for 0-25 gpm across all depth ranges. In addition, the insert tables show that fewer wells are permitted for increasingly higher yields across all depth ranges. Because only permits for wells that were likely to have been drilled (status of fully adjudicated, complete, unadjudicated, and abandoned) are shown on **Figures 8-1** through **8-6**, the number of permits on the insert matrix tables does not match the number of permits depicted on the maps.

Table 8-8. Idaho DWR groundwater permits in the Bear River Basin listed by intended use.

Well Type	Total Number of Permits	New Since 2005	Total Permitted Yield (gpm)
Municipal	0	0	0
Domestic	1	0	5
Industrial	0	0	0
Irrigation	0	0	0
Stock	0	0	0
Monitoring	0	0	0
Other	0	0	0
Multi-use	0	0	0
Total	1	0	5

Figure 5-11 shows the distribution of SWAP wells that are used for municipal and other public supply. Because public supply is one of the most important uses of groundwater resources, a more comprehensive compilation was performed for the SEO permit data and related WDEQ SWAP data on municipal and non-community public groundwater supplies.

8.7.3.3 Irrigation use permits (Figure 8-1)

Tables 8-6 through **8-8** list 90 groundwater permits for irrigation use (IRR) in the Bear River Basin, with 43 in Wyoming and 47 in Utah. **Figure 8-1** shows the distribution of likely drilled irrigation wells in the entire Bear River Basin, issued before and after January 2001. Most irrigation wells are located in rural areas and along rivers and other surface drainages where Quaternary hydrogeologic units provide adequate groundwater for this high-volume use. The depth vs. yield tables on **Figure 8-1** show that while permits have been issued for all depth categories, most irrigation well permits that list depth were permitted for depths of less than 50 feet, across a wide range of yields for both total permits and permits issued since January 2001. Most irrigation permits have no recorded depth information. **Tables 8-6** through **8-8** and the matrix tables in **Figure 8-1** illustrate that a relatively small fraction of the total number of permits in the Bear River Basin have been issued since 2001, as development may be limited in many places by the legal constraints discussed previously in this chapter, in **Chapter 1**, and in **Appendix D**. **Figure 8-1** illustrates that most permits appropriate water from wells located near the Bear River, likely targeting alluvial deposits adjacent to the river.

8.7.3.4 Livestock use permits (Figure 8-2)

Tables 8-6 through **8-8** show that 215 SEO permits and 144 UDWR permits groundwater permits have been issued solely for livestock use (STK), a quantity exceeded only by the number of domestic use and multi-use permits in the Bear River Basin. **Figure 8-2** shows the distribution of likely drilled stock wells in the Bear River Basin is-

sued before and after January 2001. Stock wells are located throughout the Bear River Basin, especially along the Bear River and its tributaries. Although, most stock wells are completed in Quaternary hydrogeologic units, some are completed in outcrops of Tertiary to Mesozoic aquifers and confining units located in areas along basin uplands. The depth vs. yield tables on **Figure 8-2** show that the largest number of total permits and permits issued since 2001 are for depths of 100 feet or less and for yields of up to 100 gpm. Many permits for stock watering have no recorded depth information.

8.7.3.5 SEO municipal use permits (Figure 8-3)

Tables 8-6 and **8-7** show that there are 19 groundwater permits issued solely for municipal use (MUN) in the Bear River Basin with 8 permits issued in Wyoming (**Table 8-6**) and 11 permits issued in Utah (**Table 8-7**). **Figure 8-3** shows the spatial distribution of likely drilled municipal wells. Most municipal permits do not contain depth data. No municipal-use permits were listed in the IDWR data.

Tables 8-9 and **8-10** distinguish 13 municipal use groundwater permits on file with the SEO by status. **Table 8-9** summarizes selected information on six municipal-use permits that have been fully adjudicated; all of these permits, with the exception of P186463 (administrative enlargement of P110471W), were issued before January 2001. **Table 8-9** includes available information on permitted yield, well depth, depth of the producing interval, and the producing hydrogeologic unit. Three of the permits in **Table 8-9** are for multiple uses. Because the "fully adjudicated" permit status indicates that the well has been inspected, the information in **Table 8-9** is presumed to be fairly accurate. The wells in **Table 8-9** produce water from bedrock aquifers, (**Plate 2**). Information on producing intervals was obtained from SWAP data, WWDC consultant reports, and SEO data.

Table 8-10 summarizes selected information on seven SEO municipal well permits listed as incomplete or complete, or do not have a status listed. **Table 8-10** includes available information on

Irrigation wells drilled since 2001

Yield (gpm)	Depth (ft)					NR	Totals
	1-49	50-99	100-499	500-999	≥1,000		
1-24	1					1	2
25-99	1						1
100-499	1					8	9
500-999						4	4
≥1,000							0
NR						29	29
Totals	3	0	0	0	0	42	45

Irrigation wells drilled before 2001

Yield (gpm)	Depth (ft)					NR	Totals
	1-49	50-99	100-499	500-999	≥1,000		
1-24	1					81	82
25-99						8	8
100-499		2				22	24
500-999						21	21
≥1,000	4		1			31	36
NR						12	12
Totals	5	2	1	0	0	175	183

Explanation

Irrigation Well Yield (gpm)
- 0 - 24
- 25 - 99
- 100 - 499
- 500 - 999
- ≥ 1000

Surface Geology
- Quaternary
- Tertiary
- Mesozoic
- Paleozoic
- Precambrian

Base Data
- ☆ City or town
- State or U.S. highway
- Interstate highway
- River or creek
- Lake or reservoir
- Township boundary
- County boundary
- State boundary

WSGS 2012
Projection: NAD 1983
UTM Zone 12N

Data Source:
Wyoming State Engineer's Office

INDEX MAP

Figure 8-1. Wyoming SEO, Utah DWR, and Idaho DWR permitted and drilled irrigation wells, Bear River Basin.
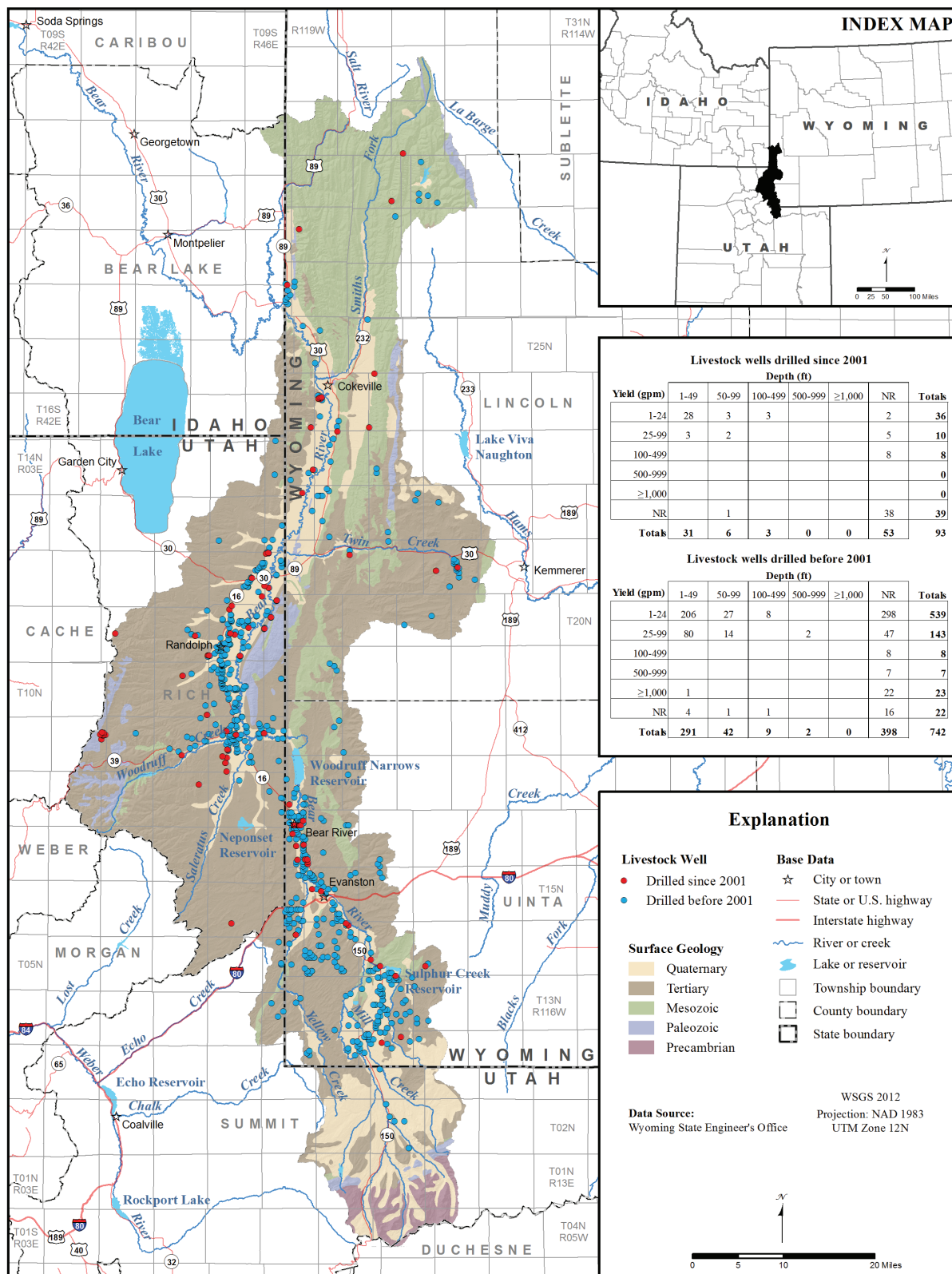
Figure 8-2. Wyoming SEO, Utah DWR, and Idaho DWR permitted and drilled livestock wells, Bear River Basin.

Livestock wells drilled since 2001

Yield (gpm)	Depth (ft)						
	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	28	3	3			2	36
25-99	3	2				5	10
100-499						8	8
500-999							0
≥1,000							0
NR		1				38	39
Totals	31	6	3	0	0	53	93

Livestock wells drilled before 2001

Yield (gpm)	Depth (ft)						
	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	206	27	8			298	539
25-99	80	14		2		47	143
100-499						8	8
500-999						7	7
≥1,000	1					22	23
NR	4	1	1			16	22
Totals	291	42	9	2	0	398	742

Explanation

Livestock Well
- Drilled since 2001
- Drilled before 2001

Base Data
- ☆ City or town
- State or U.S. highway
- Interstate highway
- River or creek
- Lake or reservoir
- Township boundary
- County boundary
- State boundary

Surface Geology
- Quaternary
- Tertiary
- Mesozoic
- Paleozoic
- Precambrian

Data Source:
Wyoming State Engineer's Office

WSGS 2012
Projection: NAD 1983
UTM Zone 12N

INDEX MAP

Figure 8-3. Wyoming SEO, Utah DWR, and Idaho DWR permitted and drilled municipal wells, Bear River Basin.

Municipal wells drilled since 2001

Yield (gpm)	Depth (ft)						Totals
	1-49	50-99	100-499	500-999	≥1,000	NR	
1-24							0
25-99						4	4
100-499	1						1
500-999							0
≥1,000							0
NR							0
Totals	1	0	0	0	0	4	5

Municipal wells drilled before 2001

Yield (gpm)	Depth (ft)						Totals
	1-49	50-99	100-499	500-999	≥1,000	NR	
1-24							0
25-99						2	2
100-499						2	2
500-999						1	1
≥1,000							0
NR							0
Totals	0	0	0	0	0	5	5

Explanation

Municipal Wells
- Drilled since 2001
- Drilled before 2001

Surface Geology
- Quaternary
- Tertiary
- Mesozoic
- Paleozoic
- Precambrian

Base Data
- ☆ City or town
- State or U.S. highway
- Interstate highway
- River or creek
- Lake or reservoir
- Township boundary
- County boundary
- State boundary

Data Source:
Wyoming State Engineer's Office

WSGS 2012
Projection: NAD 1983
UTM Zone 12N

8-171

Table 8-9. SEO fully adjudicated municipal well permits in the Bear River Basin.

Municipality or Community	Well Name	Permit Number	yield (gpm)	Depth (feet)	Permit Status	geologic unit		(feet)
Bear River	Deer Mountain #1	P65876W	26	350	Fully Adjudicated	Wasatch Fm		320-350
Bear River	Hoback Ranches #5	P84238W	25	760	Fully Adjudicated	Wasatch Fm		660-760
Bear River	Hoback Ranches #2	P84240W	25	390	Fully Adjudicated	Wasatch Fm		320-340
Cokeville	Cokeville #2	P110471W	450	173	Fully Adjudicated	Thomas Fork Fm	yes	72-119
Cokeville	Enl. Cokeville Well No. 2	P186463.0W	600	173	Fully Adjudicated	Thomas Fork Fm	yes	72-119
Cokeville	Cokeville #3	P110472W	700	175	Fully Adjudicated	Thomas Fork Fm	yes	144-173

permitted yield and well depth. All of the permits in **Table 8-10** are for multiple uses. The wells in **Table 8-10** produce water from alluvial and bedrock aquifers, (**Plate 2**).

While cancelled permits may or may not be associated with a completed well, abandoned status generally refers to a previously existing well.

8.7.3.6 Domestic use permits (Figure 8-4)

Domestic water withdrawals include non–community public water systems and rural domestic users. **Tables 8-6** through **8-8** show that groundwater permits for domestic use (DOM) outnumber permits for all other uses combined, with 418 SEO

Table 8-10. SEO municipal well permits listed with a status other than Fully Adjudicated in the Bear River Basin.

Municipality or Community	Well Name	WSEO Permit Number	Permit Yield (gpm)	Well Depth (feet)	Permit Status	New since	
Evanston	EVANSTON WELL #3	P120.0G	650	21	Incomplete		Yes
WWDC / USDI - BLM	DEER MOUNTAIN # 6	P146167.0W	100	47	Complete	Yes	Yes
Evanston	EVANSTON WELL #1	P425.0C	600	30	Incomplete		Yes
Evanston	EVANSTON WELL #2	P426.0C	500	10	Incomplete		Yes
Evanston	EVANSTON WELL #5	P588.0W	600	90			Yes
Evanston	EVANSTON WELL #8	P589.0W	500	10			Yes
Evanston	EVANSTON WELL #7	P7141.0W	600	0			Yes
Totals			3,550				

Domestic wells drilled since 2001

Yield (gpm)	Depth (ft)					NR	Totals
	1-49	50-99	100-499	500-999	≥1,000		
1-24	47	8	5				60
25-99	2	3	2			4	11
100-499						8	8
500-999							0
≥1,000							0
NR	1					153	154
Totals	50	11	7	0	0	165	233

Domestic wells drilled before 2001

Yield (gpm)	Depth (ft)					NR	Totals
	1-49	50-99	100-499	500-999	≥1,000		
1-24	345	59	22			315	741
25-99	110	22	3	1		23	159
100-499	1					14	15
500-999						2	2
≥1,000						7	7
NR	2	2				113	117
Totals	458	83	25	1	0	474	1,041

Explanation

Domestic Wells
- Drilled since 2001
- Drilled before 2001

Surface Geology
- Quaternary
- Tertiary
- Mesozoic
- Paleozoic
- Precambrian

Base Data
- ☆ City or town
- State or U.S. highway
- Interstate highway
- River or creek
- Lake or reservoir
- Township boundary
- County boundary
- State boundary

Data Source:
Wyoming State Engineer's Office

WSGS 2012
Projection: NAD 1983
UTM Zone 12N

INDEX MAP

Figure 8-4. Wyoming SEO, Utah DWR, and Idaho DWR permitted and drilled domestic wells, Bear River Basin.

permits, 416 UDWR permits, and one IDWR permit.

Figure 8-4 shows the distribution of likely drilled domestic-use permits in the entire Bear River Basin issued before and after January 2001. Most domestic wells are located in rural areas, generally outlying population centers along rivers and other surface drainages. Most wells are completed in Quaternary and Tertiary geologic units; however, domestic-use wells have also been permitted over a wide range of depths within virtually all hydrogeologic units (including confining units) throughout the Bear River Basin, pointing to the fact that useful quantities of relatively shallow groundwater can be found at many locations and that the distribution of recharge is widespread. The depth vs. yield tables on **Figure 8-4** show that basin-wide, the largest percentage of permits issued before and since January 2001 allow well depths up to 999 feet and yields up to 99 gpm. Many domestic use permits do not provide any recorded depth information.

8.7.3.7 Source Water Assessment Program (SWAP) wells and springs

The SWAP, a component of the federal Safe Drinking Water Act, is designed to help states protect public water systems (PWS) and applies to both municipal and non-community public systems. The voluntary program, administered by the WDEQ Water Quality Division (WQD), encourages the development of source-water assessments and Wellhead Protection Plans (WHP) for groundwater PWS. A source-water assessment entails determining the source-water contributing area, inventorying potential sources of contamination to the PWS, determining the susceptibility of the PWS to identified potential contaminants, and summarizing the information in a report. An important aspect of these reports relative to this study is that the producing hydrogeologic unit is commonly identified. As discussed in **Section 5.7.4**, the individual PWS reports provide valuable information on recharge areas, resource vulnerability and local sources of potential contaminants

for specific groundwater sources. The development and implementation of SWAP/WHP assessments and plans is ongoing throughout Wyoming. Additional information on the SWAP in Wyoming can be accessed at: http://deq.state.wy.us/wqd/www/SWP%20WHP/ SWAP%20FAQs.asp.

Table 8-11 provides SEO water right permit number, yield, producing unit and depth data for 17 SWAP wells in the Bear River Basin. The SEO permit numbers shown can be correlated with the wells shown in **Tables 8-9** and **8-10**. Although most wells in the SWAP database produce groundwater from alluvial deposits and Tertiary aquifers, the Cretaceous Thomas Fork Formation is also identified as a producing unit in **Table 8-11**.

Figure 5-11 shows the geospatial distribution of SWAP wells in the Bear River Basin and their relative susceptibility to potential contaminants. Insert maps on **Figure 5-11** are scaled to show more detail in areas where the wells are closely spaced.

8.7.3.8 Industrial use and CBNG permits

Table 8-6 lists 11 SEO permits for industrial (IND) use; no industrial use permits are listed for Utah or Idaho in the Bear River Basin. Primary industrial uses in the Bear River Basin have included natural gas processing, tertiary oil recovery, phosphate mining operations, sawmill operations, aggregate and gravel mining. The SEO database does not identify specific industrial uses; individual permit summaries must be reviewed for that information. Permit status for the Bear River industrial permits found in the SEO database are listed as "Incomplete" or "Not Available" so it is not possible to determine if the industrial wells are currently in use. The 2011 Bear River Water Plan (WWDO 2012) identified two current industrial uses and noted that industrial withdrawals and consumptive uses had decreased markedly since 2001 because the permitted users switched to water saving processes.

Table 8-11. WDEQ Source Water Assessment Program (SWAP) wells and springs used for municipal and non-community public water supply in the Bear River Basin.

Well Name	Public Water System ID	WSEO Permit No.	Yield (gpm)	Well Depth (ft)	Source Type	Producing Unit
Deer Mountain Ranch Subdivision	5601019-104	P146167	100	544	Well	Wasatch Fm
Deer Mountain Ranch Subdivision	5601019-101	P65876W	26	350	Well	Wasatch Fm
Deer Mountain Ranch Subdivision	5601019-103	P84238W	25	760	Well	Wasatch Fm
Deer Mountain Ranch Subdivision	5601019-102	P84240W	25	390	Well	Wasatch Fm
Town of Cokeville	5600015-102	P110471W	450	173	Well	Thomas Fork Fm
Town of Cokeville	5600015-103	P110472W	700	175	Well	Thomas Fork Fm
Evanston Lodge NO. 2588-BPOE	5601147-101	P57307W	25	370	Well	Not listed
Evanston Port-of-Entry	5601217-101	P82908W	25	218	Well	Not listed
BP America Production - Painter Reservoir	5601012-101	P72025W	25	700	Well	Wasatch Fm
BP America Production - Painter Reservoir	5601012-102	P76129W	25	701	Well	Wasatch Fm
BP America Production - Anschutz Ranch	5600790-101	P72408W	10	1510	Well	Wasatch Fm
BP America Production - Anschutz Ranch	5600790-102	P72409W	10	1680	Well	Wasatch Fm
Meadow Vista Mobile Home Park	5600897-101	P53482W	65	260	Well	Wasatch Fm
Wyoming Downs Horse Racing	5601113-102	P73997W	100	260	Well	Knight Fm (database)
Wyoming Downs Horse Racing	5601113-101	P73998W	100	240	Well	Knight Fm (database)
Yellow Creek Estates MHP	5600820-101	P51014W	125	260	Well	Wasatch Fm
Yellow Creek Estates MHP	5600820-102	P56362W	175	120	Well	Wasatch Fm

8.7.3.8.1 Groundwater use for oil and gas production

Groundwater associated with oil and gas production includes "produced water" withdrawn as a byproduct of oil and gas extraction from hydrocarbon reservoirs, and water utilized in the production and refining of petroleum resources. In some cases, produced water is used in production and refining operations; in others, water for operations is obtained from surface or underground sources. Some water plans (e.g., the 2012 Wind/Bighorn River Basin Water Plan) have treated produced water withdrawals as industrial groundwater use, while others (e.g., the 2006 Platte River Basin Water Plan) have included only water used for production and refining operations in estimates of industrial use. This study presents estimates both for groundwater volumes used for production and refining, and for produced water (**Table 8-1b**). Information

on groundwater withdrawn for production and re-fining was derived from the 2011 Bear River Basin Water Plan (WWDO 2012). Information on produced water associated with conventional oil and gas operations was obtained from the WOGCC website: http://wogcc.state.wy.us/ .

Figure 5-4 shows the locations of conventional oil and gas fields in the Bear River Basin, where groundwater is produced as a byproduct. Conventional oil and gas operations in the Bear River Basin co-produced an average of 466 ac-ft of water per year from 2003 through 2012 (**Table 8-1b**; WOGCC, 2013). There are several options for managing water co-produced with conventional oil and gas operations. The viability of these strategies, however, depends on the quality and the volume of the water produced:

- Underground injection for storage, permanent disposal, or enhanced recovery (water flooding, pressure maintenance)
- Infiltration from unlined pits and subsurface structures (tinhorns and other Class V injection facilities – generally no longer allowed)
- Evaporation from pits, landspreading, and landfarming
- Surface discharge for surface flows and associated uses:
    - domestic use (rare)
    - wildlife and livestock watering
    - wetlands, fish, and other aquatic wildlife habitat maintenance
    - irrigation
- General industrial uses:
    - drilling
    - road application and dust control
    - fire control
    - washing
    - power generation

Figures 5-4 and **5-5** show the locations of Class II and Class I injection wells, respectively, that can inject produced water from oil and gas operations. The WOGCC, BLM, and EPA permit Class II wells to operators for disposal of their own produced water. The WDEQ permits Class I wells for disposal of non-hazardous wastewaters from a

variety of sources. The WOGCC and BLM also permit evaporation pits for disposal of produced water, generally in the gas or oil field of origin. **Figure 5-6** shows the location of commercial disposal pits where produced water and other waters deemed non-hazardous are evaporated.

Produced water of suitable quality can be put to beneficial use (e.g., stock watering, agriculture, drilling and industrial dust suppression). Otherwise, produced water is primarily discharged to the surface under the regulation of WDEQ NPDES/WYPDES permits or re-injected for enhanced recovery of oil and gas from depleted reservoirs or strictly as a means of disposal. An average of 222 ac-ft/yr of water was injected from 2003 through 2012 (**Table 8-1b**; WOGCC, 2013), but it is unknown if this is produced water or groundwater withdrawn solely for enhanced recovery. Estimates of the volume of produced water discharged in the Bear River Basin under the WYPDES program are not readily available.

Produced water volumes that are discharged to the surface or put to other uses are generally considered to be partially-consumptive and, in a few cases, wholly consumptive. Almost every produced water management strategy involves some consumptive losses to evapotranspiration. On the other hand, injecting produced water into hydrogeologic units at depths where there is minimal chance of future withdrawal effectively removes it from the water budget of the basin and is wholly consumptive. In fact, most produced water probably would not have been withdrawn for any other use. Produced water discharged to the surface under a WYPDES permit generally adds to streamflows and increases the growth of vegetation. The water balance developed within this study did not consider produced water on either side of the equation.

Produced water withdrawals in the Bear River Basin are associated with conventional oil and gas operations, with lesser amounts used for coal mining. In conventional oil and gas production, groundwater is produced as a byproduct that is primarily disposed of using various methods; a smaller amount is used beneficially during production,

refining, or associated operational activities (e.g., drilling, dust suppression).

8.7.3.8.2 Groundwater use for coal mining

Coal mining operations require ground and surface water withdrawals for several mining processes. The most important include mine de-watering, mineral extraction, milling and processing operations, mine reclamation, dust suppression and personnel uses. In many cases, mining operations will reuse produced water of sufficient quality for other operations (e.g., dust suppression). Otherwise, surplus water is commonly discharged, under regulatory permit, to pits and/or surface drainage where a part is consumptively lost to evapotranspiration and the remainder returns to shallow aquifers through infiltration.

Currently the only active coal mining permit in the Bear River Basin is held by Westmoreland Kemmerer, Inc., for the Kemmerer Coal Mine, located west of Kemmerer.

8.7.3.8.3 Groundwater use for non-energy minerals development

Groundwater withdrawals for non-energy minerals development in the Bear River Basin are primarily associated with sand, gravel, and clay production. **Figure 5-8** shows the locations of groundwater permits for these uses in the Bear River Basin. Mining permits can be viewed on WDEQ Land Quality Division website: http://deq.state.wy.us/lqd_permit_public/.

8.7.3.9 Monitoring wells (Figure 8-5)

Table 8-6 lists 147 SEO groundwater permits for monitoring wells in the Bear River Basin. Monitoring wells are typically used to monitor the levels and the quality of groundwater associated with a contaminated site or a potentially contaminated site (e.g., an underground fuel storage tank) or to monitor for groundwater impacts from various activities (e.g., mining, waste management). When used for monitoring alone, these wells have no permitted yield; however, there may be a permitted

yield for other, secondary uses. The SEO required permits for monitoring wells of four inches or less in diameter only through 2004; therefore, the data for these permits is incomplete.

Figure 8-6 shows the distribution of likely drilled SEO monitoring well permits in the Bear River Basin and permits issued before and after January 2001. Most monitoring wells are located near Evanston or the Kemmerer coal mine. The depth vs. yield tables on **Figure 8-6** show that while permits have been issued for all depth categories, by far the largest number were issued for depths of 0 to 50 feet reflecting monitoring of the shallow water table aquifers that are most susceptible to contamination. Although, recorded depths are available for most monitoring wells in the database, only one well permit includes recorded yield data. Many of the monitoring wells were permitted after 2001; however, as discussed above, even this number is probably understated, per the 2004 SEO policy change.

8.7.3.10 Permits for other and miscellaneous uses (Figure 8-6)

Table 8-6 indicates that 112 permits have been issued for "other" uses and 408 permits for "multi-use" wells have been granted by the SEO (**Table 8-6**). Multi-use permits list more than on use; for example a permit that shows both "domestic and "stock" uses is a multi-use permit. **Table 8-7** lists 134 and 229 UDWR permits issued for "other" and "multi-use" wells in the Utah portion of the basin. Some of the "multi-use" permits issued test wells are generally employed for aquifer testing to determine aquifer characteristics. Information on specific miscellaneous use and test wells may be found in some permit applications available online. However, developing detailed information for specific miscellaneous use and test wells was beyond the scope of this study.

Figure 8-6 shows the distribution of likely drilled wells permitted for "miscellaneous use" and "other" wells in the Bear River Basin, and permits issued before and after January 2001. "Miscellaneous use" and "other" wells are located throughout the Bear River Basin and are generally concentrated in mineral development areas and along rivers and

Monitoring wells drilled since 2001

Yield (gpm)	Depth (ft)						
	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24							0
25-99							0
100-499							0
500-999							0
≥1,000							0
NR	41	3					44
Totals	41	3	0	0	0	0	44

Monitoring wells drilled before 2001

Yield (gpm)	Depth (ft)						
	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24						1	1
25-99							0
100-499							0
500-999							0
≥1,000							0
NR	59	9	7			16	91
Totals	59	9	7	0	0	17	92

Explanation

Monitoring Well Depth (ft)
- 1 - 49
- 50 - 99
- 100 - 499

Surface Geology
- Quaternary
- Tertiary
- Mesozoic
- Paleozoic
- Precambrian

Base Data
- ☆ City or town
- State or U.S. highway
- Interstate highway
- River or creek
- Lake or reservoir
- Township boundary
- County boundary
- State boundary

WSGS 2012

Data Source:
Wyoming State Engineer's Office

Projection: NAD 1983
UTM Zone 12N

Figure 8-5. Figure 8-5. Wyoming SEO, Utah DWR, and Idaho DWR permitted and drilled monitoring wells, Bear River Basin.

Miscellaneous and Other wells drilled since 2001

Yield (gpm)	Depth (ft)						
	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	4	2	2			1	9
25-99	2					2	4
100-499						8	8
500-999							0
≥1,000							0
NR						7	7
Totals	6	2	2	0	0	18	28

Miscellaneous and Other wells drilled before 2001

Yield (gpm)	Depth (ft)						
	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
1-24	8	6	5			35	54
25-99	2	2	11			14	29
100-499	1		2			14	17
500-999						1	1
≥1,000						2	2
NR	1	1	2			81	85
Totals	12	9	20	0	0	147	188

Explanation

Miscellaneous and Other Wells
- Drilled since 2001 (red)
- Drilled before 2001 (blue)

Surface Geology
- Quaternary
- Tertiary
- Mesozoic
- Paleozoic
- Precambrian

Base Data
- ☆ City or town
- State or U.S. highway
- Interstate highway
- River or creek
- Lake or reservoir
- Township boundary
- County boundary
- State boundary

INDEX MAP

Data Source:
Wyoming State Engineer's Office

WSGS 2012
Projection: NAD 1983
UTM Zone 12N

Figure 8-6. Wyoming SEO, Utah DWR, and Idaho DWR permitted and drilled miscellaneous and other wells, Bear River Basin.

larger surface drainages. The depth vs. yield tables on **Figure 8-6** show that most groundwater permits have been issued for depths up to 500 feet and for yields of 0 to 99 gpm for both total permits and permits issued since 2001. Most of these permits have no recorded depth.

8.7.3.11 Hydrothermal use

The Bear River Basin has no potential for high-grade geothermal energy development.

8.8 Groundwater interference/ interconnection with surface water

The potential for interference between wells and well fields located within areas of interconnected surface and groundwater that exhibit historically high levels of drawdown must be considered when assessing the historic, current, and future use of groundwater in the Bear River Basin. Generally, these issues are addressed within the state's institutional and regulatory framework for groundwater development (**Chapter 1**), primarily by the Amended Bear River Compact of 1978.

8.8.1 Interference between wells

As a well withdraws water from an unconfined aquifer, it depresses the groundwater level around the well casing in a generally radial configuration, called a "cone of depression". In areas where several actively pumping wells are sited in close proximity to each other, their respective cones of depression may overlap and "well interference" may result. If well interference becomes excessive, aquifer water levels may drop below the depth of some wells causing conflicts between users. In Wyoming, the SEO may address cases of excessive well interference by recommending the formation of a groundwater control area wherein groundwater uses are actively managed by a groundwater control area advisory board. According to Wyoming State Statute WSS 41-3-912, a "control area" can be designated by the Board of Control on the recommendation of the State Engineer for any of the following reasons:

- The use of underground water is approaching a use equal to the current recharge rate.

- Groundwater levels are declining or have declined extensively.
- Conflicts between users are occurring or are foreseeable.
- The waste of water is occurring or may occur.
- Other conditions exist or may arise that require regulation for the protection of the public interest.

Currently, there are no control areas designated in the Bear River Basin. Additional information about groundwater control areas can be found online at: https://sites.google.com/a/wyo.gov/seo/groundwater/groundwater-control-areas-advisory-boards

8.8.2 Interconnection between groundwater and surface water

Surface flows are subject to strict water rights, and conflicts occur where groundwater extraction affects surface flow. Although the Wyoming Constitution establishes that all surface water and groundwater within Wyoming's borders is owned by the state, the right to put surface water and groundwater to beneficial use is permitted via water rights issued by the Wyoming SEO and adjudicated by the Wyoming Board of Control. Surface water resources are subject to interstate agreements that limit how much streamflow can be depleted before leaving the state. Furthermore, conflicts among users within the state or across state lines can occur where groundwater extraction may affect surface flows. Although interconnection between groundwater and surface water is not currently a significant water rights issue in the Bear River Basin, it could become a point of contention in the future as the basin's population grows.

To avert present and future conflicts over the allocation and use of water flows within the Bear River Basin, the states of Idaho, Utah and Wyoming agreed to the Amended Bear River Compact in 1978. The compact divides water administration in the Bear River among three geographically defined divisions. The Upper Division encompasses the reach of the Bear River that extends from its headwaters in the Uinta Mountains to the Pixley diversion dam in sec. 25, T. 23 N., Range 120 W. of the

Sixth Principal Meridian in Wyoming. During a compact defined water emergency in the Upper Division, percentage allocations are made to the Utah and Wyoming Sections and distribution of divertible flow is managed by diversion by the two states. The Central Division extends from below Pixley Dam to the Stewart diversion dam in sec. 34, T. 13 S., R. 44 E., Boise Base Meridian in Idaho; during a water emergency, divertible flow is allocated by percentage to Wyoming and Idaho. In the Lower Division, which extends from the Stewart Dam to the Great Salt Lake, divertible flows are allocated by a commission approved delivery schedule.

The portion of the Bear River drainage basin, examined in this report, consists of the entire Upper Division and those parts of the Central Division that are tributary to the Bear River upstream of the Idaho-Wyoming border (**Figure 3-1**). **Appendix D** (SEO, 2006) contains a copy of the Amended Bear River Compact (1978). The compact is administered by the Bear River Commission (http://www.bearrivercommission.org/) composed of three commissioners from each signatory state. The Interstate Streams Division of the SEO, in conjunction with the Water District IV staff, administers the provisions of the compact that fall under the authority of the state of Wyoming.

Along with the distribution of water specified for each of the divisions, Article VI of the compact allocates an additional 13,000 ac-ft annual total of surface and connected groundwater each to Wyoming and that portion of Utah above Stewart Dam for beneficial uses applied on or after January 1, 1976. Historically, Wyoming has used only a small portion of this additional allocation, so it is likely that future groundwater development in the Bear River Basin allow Wyoming to develop and utilize its 13,000 ac-ft allocation. In Wyoming, the SEO monitors surface water and connected groundwater depletions owing to the additional allocation.

Chapter 9
Looking to the Future

Karl Taboga, Paul Taucher, Keith Clarey
and Lisa Lindemann

The purpose of this chapter is to discuss future water use opportunities in the Bear River Basin. This issue was examined in detail in the previous Bear River Basin Water Plans (WWC Engineering, and others, 2007; Forsgren Associates, 2001; Wyoming Water Development Office, 2012). This study provides the most current information available about the future focus and direction of Bear River Basin groundwater development projects.

The discussions of technical concepts and Thrust Belt geology previously covered in this study provide the background needed to understand the practical considerations that shape the conceptualization, design, and successful completion of a water resource development project. **Chapter 5** opened with the definition of several elementary, hydrogeologic concepts that are crucial to understanding basic groundwater science. **Section 5.1.3** introduced the dynamics of groundwater recharge, discharge, and flow and summarized the hydrogeologic settings that are characteristic of the Thrust Belt. Future groundwater development in the Bear River drainage is not only physically limited by Thrust Belt hydrogeology but is also legally bound by the provisions of the Amended Bear River Compact of 1978 (**Appendix D**). Specific groundwater development projects are discussed in **Section 9.1**, and recommendations for future updates of this Groundwater Determination Technical Memorandum are presented in **Section 9.2**.

Additional supporting information for the project assessments contained in this chapter can be found in several, previous Chapters of this study:

- Hydrogeology is discussed at length in **Chapters 5** through7 and illustrated in **Plate 5**.
- Groundwater chemical characteristics are summarized in **Chapter 7** and **Appendices E** through **H**.
- Recent and historic development patterns specified by beneficial use, obtained from the State Engineer's Office (**Chapter 8**).
- Studies published by the USGS (**Chapter 7**) and Wyoming Water Development

Commission (**Appendix B**) that examine the development potential of specific aquifers.
- The 2001 Water Plan for the Bear River Basin (Forsgren Associates, 2001), the 2011 Water Plan (Wyoming Water Development Office, 2012) and associated technical memoranda, as well as the 2007 State Water Plan (WWC Engineering and others, 2007), identify potential groundwater development projects considered prior to the completion dates of those studies. Many of the opportunities examined in those publications may be under current development or will become more viable in the future as financial factors and technological improvements allow.
- The Water Resources Data System Library, specifically the WWDC Projects and Studies Web page, contains hundreds of water development reports for projects completed over the last 40 years for localities throughout Wyoming.

In this chapter, only development projects that are designed with the primary objective of producing potable groundwater are discussed. Projects that may produce groundwater as a value added byproduct of other activities, such as oil and gas production or in-situ mineral extraction, are not considered.

9.1 Issues affecting future groundwater development

- Water availability – A groundwater resource must be legally, economically, and physically available. In the Bear River Basin, groundwater availability is controlled by the hydrogeology of the Thrust Belt as well as the Amended Bear River Compact of 1978.

- Funding – Groundwater development projects are expensive and most Wyoming municipalities do not have the funds required to plan, carry out and complete development programs. Funding for these

projects, therefore, has to be obtained from governmental agencies. The primary water development funding agencies in Wyoming are the WWDO, DEQ, and the U.S. Department of Agriculture.

- Stakeholder involvement – The successful completion of any groundwater project requires the involvement of the stakeholders who have interests in the development or preservation of the water resource. Stakeholders include current and future water users; landowners; business representatives; attorneys; scientists; engineers; environmentalist groups; sportsmen; holders of competing water rights; municipal, state, and federal regulatory agencies; and others. Stakeholder support for or opposition to a water development project depends on the nature, benefits, costs, and perceived impacts of the particular project. The project will likely incur substantial cost increases and time delays if legal challenges are filed by stakeholders opposed to development.

- Interstate compacts - The Amended Bear River Compact of 1978 regulates water use in the Bear River Basin. The provisions of the compact are primarily administered by the SEO.

- Water quality – The successful completion of a groundwater development project depends on whether the quality of the water produced from the targeted resource meets the requirements of the intended beneficial use(s). State and federal laws may mandate water quality requirements for certain beneficial uses or may, alternately, be used as a reference measure for others. For example, the National Primary Drinking Water Regulations (**Table 5-2**) established by the Environmental Protection Agency (EPA) under provisions of the Safe Drinking Water Act are legally enforceable standards for public water systems (PWS) but do not regulate water quality in private groundwater wells that serve fewer than 25 people. Still, water quality in private wells is frequently evaluated in comparison to the Maximum Contaminant Levels (MCL) contained in the EPA regulations.

- Environmental regulation – Water development projects in Wyoming are subject to regulation under the provisions of state and federal environmental laws including:
  - Wyoming Environmental Quality Act – the principal state environmental law that created the Wyoming Department of Environmental Quality repealed the state's existing environmental laws (in 1973) and replaced them with the provisions of the new act.
  - Endangered Species Act – a federal environmental law designed to protect imperiled plant and animal species from extinction. The ESA is administered under the Endangered Species Program of the U.S. Fish and Wildlife Service and the National Marine Fisheries Service of the National Oceanic and Atmospheric Administration (NOAA).
  - National Environmental Policy Act (NEPA) – a main federal law that established national environmental policy. It requires federal agencies in the executive branch to write Environmental Impact Statements (EIS) and Environmental Assessments (EA) that examine anticipated impacts to the environment resulting from proposed federal agency actions.
  - Clean Water Act – the principal federal law that governs pollution in the nation's surface waters. The CWA does not regulate groundwater pollution directly. The Water Quality Division of DEQ regulates the discharge of pollutants to surface waters under the CWA.

- Safe Drinking Water Act – the primary federal law that ensures safe drinking water supplies for the public. The SDWA covers public water supplies but does not apply to private wells that serve less than 25 people. The EPA administers and enforces provisions of the SDWA.

9.1.1 Groundwater development potential in areas subject to the Amended Bear River Compact of 1978

The Amended Bear River Compact of 1978 divides water administration in the Bear River among three geographically defined divisions. The Upper Division encompasses the reach of the Bear River that extends from its headwaters in the Uinta Mountains to the Pixley diversion dam in Sec. 25, T. 23 N., R. 120 W. of the Sixth Principal Meridian in Wyoming. During a compact defined water emergency in the Upper Division, percentage allocations are made to the Utah and Wyoming sections and distribution of divertible flow is managed by diversion by the two states. The Central Division extends from below Pixley Dam to the Stewart diversion dam in Sec. 34, T. 13 S. R. 44 E. Boise Base and Meridian in Idaho; during a water emergency, divertible flow is allocated by percentage to Wyoming and Idaho. In the Lower Division, which extends from the Stewart Dam to the Great Salt Lake, divertible flows are allocated by a commission approved delivery schedule.

The portion of the Bear River drainage basin examined in this report consists of the entire Upper Division and those parts of the Central Division that are tributary to the Bear River upstream of the Idaho-Wyoming border (**Fig. 3-1**). **Appendix D** (SEO, 2006) contains a copy of the Amended Bear River Compact (1978). The compact is administered by the Bear River Commission (http://www.bearrivercommission.org/), composed of three commissioners from each signatory state. The Interstate Streams Division of the SEO, in conjunction with the Water District IV staff, administers the provisions of the compact that fall under the authority of the state of Wyoming.

Along with the distribution of water specified for each of the divisions, Article VI of the compact allocates an additional 13,000 ac-ft annual total of surface and connected groundwater each to both Wyoming and that portion of Utah above Stewart Dam for beneficial uses applied on or after January 1, 1976. Historically, Wyoming has used only a small portion of this additional allocation, so it is likely that future groundwater development in the Bear River Basin will allow Wyoming to develop and utilize its 13,000 ac-ft allocation. In Wyoming, the SEO monitors surface water and connected groundwater depletions owing to the additional allocation.

Appendix B contains a chronological summary of groundwater development related projects sponsored by the WWDC in the Bear River Basin since 1973. Information contained many of these studies was used to describe, in detail, the physical and chemical characteristics of the basin's hydrogeologic units in **Chapter 7**. **Appendix B** summarizes the following groundwater development information for WWDC projects in the Bear River Basin:

- References to the study(s) – full citations are included in the References
- Location, including as appropriate: town, county, rural area, irrigation district, well site, etc.
- Aquifers involved in the study
- Project descriptions of development potential of area(s) and aquifer(s) and development drilling project(s)
- Summary of results
- Current project status

9.1.2 Future water use opportunities

Chapter 8 of the 2011 Bear River Basin Water Plan (Wyoming Water Development Office, 2012) provides a detailed discussion of future water use opportunities with the intention that their implementation would result in expanded water supplies that could be used to meet current and future water demands. These issues were initially developed by the Bear River Basin Advisory Group (Bear River BAG) in 1998 and

updated in 2005. Their recommendations are available online at: http://waterplan.state.wy.us/BAG/bear/meetingrecords.html and identify both structural and non-structural water development opportunities. Structural opportunities are projects that involve the design and construction of new water storage and conveyance infrastructure or the modification and improvement of existing infrastructure to include new or upgraded groundwater development, enlarging reservoirs, trans-basin diversion programs, or improving existing water distribution systems. Non-structural opportunities do not require modifications to infrastructure but involve programmatic changes in water use and management such as water conservation programs, improvements in efficiency-of–use, water-banking, and improved reservoir operation.

This report briefly examines new groundwater resource development in the Bear River Basin.

9.1.3 Potential new groundwater development prospects

Article VI of the Amended Bear River Compact allocates an additional 13,000 ac-ft annual total of surface and connected groundwater to both Wyoming and that portion of Utah above Stewart Dam for beneficial uses applied on or after January 1, 1976. Historically, Wyoming has used only a small portion of this additional allocation, so it is likely that future groundwater development in the Bear River Basin will be allowed in order for Wyoming to develop and utilize its 13,000 acre-feet allocation. Unlike some Wyoming river basins such as the Platte (Taucher and others, 2013), all groundwater in the Bear River Basin is considered to be hydrologically connected to surface water flows and the compact does not consider that some bedrock aquifers may be hydraulically isolated from the river. Future groundwater development and planned depletions will have to proceed in compliance with the 13,000 ac-ft allocation.

Virtually all aquifers and some confining units in the Bear River Basin have some physical potential for development (**Pl. 2** and **Table 9-1**), depending on the requirements for quantity and quality

called for by the specified beneficial use(s) and on technical limitations. The Quaternary Bear alluvial aquifer remains available for future groundwater development. Additionally, Mesozoic and Late Paleozoic bedrock aquifers are underutilized and may be prime targets for future development especially within or in close proximity to outcrop areas where recharge is actively occurring, residence times are low and water quality is good. Although well yields could be expected to range from 10 to 500 gpm in these aquifers, water quality and susceptibility to surface sources of contamination (e.g. irrigation return flows and spills from energy development activities) should be considered in evaluating development prospects. **Table 9-1** summarizes further groundwater development potential in the basin's main hydrogeologic units.

9.1.4 Recent WWDC groundwater development prospects

An examination of recent (since 2001) WWDC groundwater development projects provides, perhaps, the most realistic evaluation of future groundwater development in the Bear River Basin. The recent projects are driven by present and expected future needs of municipalities that are likely to experience population adjustments in the coming years as the economy of Wyoming becomes increasingly centered on energy production and continues to focus on the economic development of groundwater resources relative to the issues discussed in **Section 9.1**. Recent groundwater projects from the WRDS water library are presented to illustrate viable future prospects, some of which have been identified for several years, for new and additional public-support groundwater development in the Bear River Basin:

9.1.4.1 North Uinta

The North Uinta County Improvement and Service District (Town of Bear River) conducted a multi-phase, feasibility investigation (Trihydro, 2003) of the feasibility and benefits of developing a groundwater supply from the Wasatch Formation near three existing public water supply wells located near the Deer Mountain Subdivision. A

Table 9-1. Generalized groundwater development potential for major regional aquifer systems in the Bear River Basin (modified from WWC Engineering and others, 2007; Wyoming Water Development Office, 2012).

	System	Location	Well yields	Major aquifers	General potential for new development
Quaternary	Alluvial	Throughout Bear River Basin	Small to large	Unconsolidated deposits	Good to very good
	Non-alluvial	Throughout Bear River Basin	Small to moderate	Primarily unconsolidated terrace deposits	Good to very good
Tertiary	Late	Scattered small outcrops west edge of basin	Small to moderate	Salt Lake	Good - little yield data
	Early	Widespread outcrops in south and central basin	Small to large	Fowkes, Wasatch, Evanston, and equivalents	Good to very good
Mesozoic	Late Cretaceous	Scattered outcrops south and central basin	Small to moderate	Evanston, Adaville, Frontier	Fair to very good – little yield data
	Early Cretaceous	Widespread outcrops throughout basin	Small to moderate	Bear River, Thomas Fork, Gannett	Fair to good - some marginal yields
	Triassic/ Jurassic	Outcrops on uplands and flanks in central and north basin	Moderate to large	Twin Creek, Nugget, Thaynes	Good to very good
Paleozoic	Late	Exposed on uplifts in north basin	Small to large	Phosphoria, Madison, Amsden, Wells	Fair to Very good – some marginal water quality
	Early	Outcrops largely absent	Unknown	Flathead, Bighorn, Gallatin	Fair – outcrops largely absent

test well, Deer Mountain #6, was designed and completed at a depth of 544 feet in the Wasatch Formation. Aquifer testing and water quality analyses indicated that the well could serve as PWS well for the Town of Bear River. Subsequently, the Deer River #6 well was connected to the town's PWS via a new water transmission line.

9.1.4.2 Evanston/Bear River regional water system

Sunrise Engineering (2005) conducted a Level II study under contract to the WWDC to examine the feasibility of implementing a regional water system with water supplied by the City of Evanston to the Town of Bear River. The study

evaluated water rights, water storage, transmission infrastructure, and water demand. Analyses of economic, environmental, engineering, and facility administration factors were also conducted. Conceptual designs and cost estimates were developed as well. The study concluded that a regional system could provide needed water supplies to the Town of Bear River. Subsequently, the regional system was constructed and is currently in operation. While the water supplied by this system comes from Bear River surface flows, this WWDC project eased groundwater demands in North Uinta County and is an example of successful regional water system development.

9.1.5 Current WWDC and SEO projects

Currently, neither WWDC nor SEO are conducting large scale groundwater development projects in the Bear River Basin. Applications submitted to the SEO largely are usually for domestic and stock well permits.

9.1.6 Groundwater interference and interconnection with surface water

Other factors that must be considered for new groundwater projects in development are the potential for interference between wells or well fields completed in the same aquifer, excessive drawdowns in over-utilized aquifers, and interconnections between groundwater and surface water. These issues have been encountered and in some cases, addressed in the Bear River Basin. The WWDC groundwater development project in North Uinta County (Trihydro, 2003) reported a case of well interference between a newly installed test well and a previously completed PWS wells. Well interference, alone, does not necessarily present significant problems to a public water system depending on several factors including, but not limited to, the physical and hydrogeologic properties of the target aquifer, construction of the production wells, and the timing and rate(s) of well production. In aquifers that possess high degrees of secondary (fracture) permeability, well interference may be unavoidable over the scale of several miles. In many cases, municipal water supply personnel, who are aware of well interference effects in their facilities, effectively manage them by adjusting well pumping times and rates, or periodically switching to other sources of municipal water.
Excessive drawdown, or groundwater depletion, in over-utilized aquifers has become a national concern (Konikow, 2013). Currently, this does not appear to be an issue of regional concern in the Bear River Basin.
Finally, the interconnection between groundwater and surface water in the Bear River Basin is addressed in the Amended Bear River Compact by treating both surface water and groundwater withdrawals as depletions of the basin's water resources.

9.2 Recommendations for future updates

The quality of the Wyoming State River Basin water plans is limited by the availability of data and the institutional resources used to develop the compiled information in a form that is readily accessible and useful to stakeholders in groundwater development. While some information (e.g., hydrogeology studies, SEO groundwater permit, data from the DEQ and other agencies) is generally available for all basins, other information (e.g. regional groundwater modeling) does not exist. The quantity, accuracy, and completeness of available groundwater information vary between and within the major drainage basins of Wyoming.

The purpose(s) of updating an Available Groundwater Determination can be to include new information generated since the previous determination, to include older information not initially provided and to utilize continuously improving technology to maximize the value of the relevant information that is presented. While information in some areas will grow slowly (e.g., mapping of geologic and hydrogeologic units), other information (e.g., SEO and other agency data) requires regular updates to maintain its utility.

9.2.1 Data challenges

Computing capabilities will continually improve but will always be limited by the availability and reliability of the input data. The quality of a compilation study such as this relies on the quality of the available data. The development of a comprehensive statewide database for water quality and aquifer physical characteristics would greatly assist Wyoming water professionals to manage and protect the state's valuable water resources.

Currently, hydrogeologic and hydrogeochemical data exist that could be integrated into a more comprehensive and evolving groundwater database for Wyoming. For example, DEQ collects copious amounts of groundwater data for site-specific investigations of contaminated sites, for issuing

industrial permits (e.g. mining, UIC, waste and wastewater management), and for monitoring for potential impacts. The SEO collects groundwater information from selected wells. The USGS, WOGCC, BLM, EPA, counties, municipalities, other agencies, and private entities all collect hydrologic information for a variety of activities and purposes. However, coordination between the various entities collecting groundwater information is generally lacking, and clearly there is abundant relevant information that was not and is not accessible for this study and groundwater determinations in other basins. While the quality of some of this information may not be consistent with the standards described in **Chapter 7**, those data could be qualified. Although, some data (e.g., on contaminated samples) would not be representative of natural groundwater, and some water quality analyses (e.g., for contaminated sites and industrial site monitoring) will be for constituents not commonly used to characterize natural groundwater quality; nevertheless, a comprehensive database would be useful.

Ongoing revision and maintenance of a comprehensive groundwater information database where data are continually being generated by numerous entities would be a substantial project, requiring a continuing commitment of resources by federal, state, and local agencies and is certainly easier described than done. As interest in groundwater resources increases, so will justification for such a program.

9.2.2 Current and future research efforts

This study is a compilation of previous investigations conducted primarily by state and federal agencies and consultants. Any significant advancement in the development of the conceptual model of the hydrogeology of the Bear River Basin or its Laramide sub-basins will require further original research, most likely conducted by academic investigators; USGS water scientists; or by consultants employed by the WWDO, SEO, or Wyoming municipalities. The recent formation of the Wyoming Center for Environmental Hydrology and Geophysics

(WyCEHG) should prove to be particularly valuable to a better understanding of groundwater resources in the Bear River Basin. Funded for a five year period by the National Science Foundation, WyCEHG efforts are specifically targeted to advancing research in western hydrologic systems using advanced geophysics and remote sensing technologies. The stated goals of WyCEHG are:

- **To improve understanding of mountain front hydrology** by characterizing the processes that partition water into streams, soils, plants, rivers and aquifers in several locations throughout the state.
- **To improve understanding of how disturbances affect water flux** by studying effects on hydrological systems from climate change, bark beetle infestations, and energy extraction.
- **To improve integrated modeling of the fate and transport of water** by creating integrated computer models that will provide the scientific knowledge and tools for improved prediction of hydrological processes.
- **To provide cutting edge resources and tools** for educators and watershed managers in the state.
  Further information can be obtained from the website for WyCEHG which can be accessed at: http://www.uwyo.edu/epscor/wycehg/.

The recharge calculations based on the surface outcrop area of hydrogeologic units and the SDVC map of recharge (Hamerlinck and Arneson, 1998), contained in **Section 6.2**, went beyond summarizing existing information by using the data to estimate the groundwater resource. The recharge evaluation in this study could easily be updated and the results refined as new data is collected, with a relatively low-level commitment of resources. The estimation of recharge can be enhanced by numerical modeling in selected areas that includes additional variables that affect infiltration and recharge (**Section 5.1.3**).

Furthermore, there are several areas where additional geologic mapping would develop useful

information for future Bear River Basin Water Plan updates. More detailed geologic mapping would better define the hydrogeologic role of the basin's geologic, further identify areas where groundwater and surface water may be interconnected, and determine areas where vertical recharge may be enhanced by fracture permeability.

References

Ahern, John, Collentine, Michael, and Cooke, Steve, 1981, Occurrence and characteristics of ground water in the Green River Basin and Overthrust Belt, Wyoming: Laramie, University of Wyoming Water Resources Research Institute, v. V-A, 123 p., and V-B (6 pl.).

Aller, L., T. Bennett, J.H. Lehr, and R.J. Petty, 1985, DRASTIC: A Standardized System for Evaluation of Groundwater Pollution Potential Using Hydrogeologic Settings. USEPA 600/2-85/0108. Ada, Okla.: USEPA, Robert S. Kerr Environmental Research Laboratory

American Society of Civil Engineers (ASCE) Task Committee for Sustainability Criteria, 1998, Sustainability criteria for water resource systems: ASCE Publications, 253 p.

Back, William, 1966, Hydrochemical facies and ground-water flow patterns in northern part of Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 498–A, 42 p.

Barlow, P.M., and Leake, S.A., 2012, Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p.

Bartolino, J.R., and Cunningham, W.L., 2003, Ground-water depletion across the nation: U.S. Geological Survey Fact Sheet 103–03, 4 p.

Bartos, T.T., Eddy-Miller, C.A., and Hallberg, L.L., 2009, Occurrence of pesticides in ground water of Wyoming, 1995–2006: U.S. Geological Survey Scientific Investigations Report 2009−5024, 72 p.

Bartos, T.T., and Hallberg, L.L., 2010, Green River Basin groundwater and hydrogeologic units, Chapter 5, in Clarey, K.E., Bartos, T.T., Copeland, David, Hallberg, L.L., Clark, M.L., and Thompson, Melissa, Available groundwater determination technical memorandum, Green River Basin water plan II, Groundwater study level 1 (2007–2009): Laramie, Wyo., prepared by the Wyoming State Geological Survey for the Wyoming Water Development Commission, p. 5-1–5-93

BBC Consulting, Edward Harvey and Doug Jeavons. 2001 Bear River Basin Water Plan Technical Memorandum Appendix Q, Future Economic and Demographic Scenarios. Wyoming Water Development Commission, Cheyenne, Wyoming.

Bear River Compact, as amended, 1978. http://legisweb.state.wy.us/statutes/titles/title41/c12a01.htm

Bedessem, M.E., Casey, B., Frederick, K., and Nibbelink, N., 2003, Phase I: Aquifer prioritization, Final report: Prepared for the Wyoming Department of Environmental Quality by the University of Wyoming Department of Civil and Architectural Engineering, Laramie, Wyo., variously paged.

Belitz, K. and Bredehoeft, J.D, 1988, Hydrodynamics of Denver Basin: Explanation of Subnormal Fluid Pressures: AAPG Bulletin, v.72, no. 11, p. 1334 – 1359.

Berry, D.W., 1955, Reconnaissance of the geology and ground-water resources of the Cokeville area, Lincoln County, Wyoming: U.S. Geological Survey Open-File Report 55–15, 11 p.

Bohn, H.L., McNeal, B.L., and O'Connor, G.A., 1985, Soil chemistry: New York, John Wiley and Sons, 341 p.

Boner, F.C., Lines, G.C., Lowry, M.E., and Powell, J.E., 1976, Geohydrologic reconnaissance and measurement of perennial streams crossing outcrops of the Madison Limestone, northeastern Wyoming: U.S. Geological Survey Open-File Report 75–614, 64 p., 1 pl.

Bradley, W.H., 1964, Geology of the Green River Formation and associated Eocene rocks in southwestern Wyoming and adjacent parts of Colorado and Utah: U.S. Geological Survey Professional Paper 496–A, 86 p.

Bruce, C.E., 1988, Jurassic Twin Creek Formation—A fractured limestone reservoir in the Overthrust Belt, Wyoming and Utah, in Goolsby, S.M., and Longman, M.W., eds., Occurrence and petrophysical properties of carbonate reservoirs in the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 105–120.

Cerny, J.H., and Hagen, T.F., 1992a, Road Hollow-Bridger Fork Unit, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin and Overthrust Belt: Wyoming Geological Association, p. 264.

Cerny, J.H., and Hagen, T.F., 1992b, Road Hollow-

Collett Creek Unit, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin and Overthrust Belt: Wyoming Geological Association, p. 265.

Chase, J.D., Stilwell, D.P., and Bentley, R.D., 1992a, Anschutz Ranch East (east lobe), in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin and Overthrust Belt: Wyoming Geological Association, p. 20–22.

Chase, J.D., Stilwell, D.P., and Bentley, R.D., 1992b, Bessie Bottom, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin and Overthrust Belt: Wyoming Geological Association, p. 34–35.

Clarey, K.E, 2011, Bear River Basin Plan Update, Groundwater Technical Memorandum (Update of 2001 Bear River Basin Plan), Appendix A, Groundwater availability: Wyoming Water Development Commission, variously paged.

Colorado State University, 2013, Understanding Plant Water Use; Evapotranspiration (ET): available online at: http://ccc.atmos. colostate. edu/~coagmet/extended_etr_about.php.

Cooley, M.E., 1984, Artesian pressures and water quality in Paleozoic aquifers in the Ten Sleep area of the Bighorn Basin, north-central Wyoming: U.S. Geological Water-Resources Investigations/ Open-File Report 84–621, 74 p.

Cooley, M.E., 1986, Artesian pressures and water quality in Paleozoic aquifers in the Ten Sleep area of the Bighorn Basin, north-central Wyoming: U.S. Geological Survey Water-Supply Paper 2289, 54 p., 5 pl.

Curtis, J., 2004, Wyoming Climate Atlas: Wyoming Water Development Commission, Cheyenne, Wy. 328p.

Dana G. F., 1962, Groundwater reconnaissance study of the State of Wyoming, Part 4. Green River basin: Prepared for Wyoming Natural Resource Board, Cheyenne, 355 p.

Doremus, D.M., 1986, Groundwater circulation and water quality associated with the Madison aquifer in the northeastern Bighorn Basin, Wyoming: Laramie, University of Wyoming, M.S. thesis, 81 p.

Dover, J.H., 2007, Geologic map of the Logan 30' x 60' quadrangle, Cache and Rich Counties, Utah, and Lincoln and Uinta Counties, Wyoming: Utah Geological Survey, Miscellaneous Publication 06-8DM, scale 1:100,000.

Dover, J.H., and M'Gonigle, J.W., 1993, Geologic map of the Evanston 30' x 60' quadrangle, Uinta and Sweetwater Counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I–2168, map scale 1:100,000, 1 sheet.

Eddy-Miller, C.A., Bartos, T.T., and Taylor, M.L., 2013, Pesticides in Wyoming groundwater, 2008–10: U.S. Geological Survey Scientific Investigations Report 2013–5064, 45 p.

Eddy-Miller, C.A., and Norris, J.R., 2000, Pesticides in ground water—Lincoln County, Wyoming, 1998–99: U.S. Geological Survey Fact Sheet FS–033–00, 4 p.

Eddy-Miller, C.A., and Remley, K.J., 2004, Pesticides in ground water—Uinta County, Wyoming, 2002–03: U.S. Geological Survey Fact Sheet 2004–3093, 4 p.

Eddy-Miller, C.A., Plafcan, Maria, and Clark, M.L., 1996, Water resources of Lincoln County, Wyoming, with a section on Water-right administration, by R.G. Stockdale, Wyoming State Engineer's Office: U.S. Geological Survey Water-Resources Investigations Report 96–4246, 131 p., 3 pl.

Eyer, J.A., 1969, Gannett Group of western Wyoming and southeastern Idaho: American Association of Petroleum Geologists Bulletin, v. 53, no. 7, p. 1368–1390.

Fernandez, Mark, and Andrews, Jeanette, 1979, Whitney Canyon, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin: Wyoming Geological Association, p. 420–421.

Fetter , C. W., 2001 Applied Hydrogeology, 2001, 4th Edition, Prentice Hall, Upper Saddle River, N.J. 598 p.

Forsgren Associates, Inc., 1993a, Cokeville Water Supply Level II Study, Final Report: prepared for the Wyoming Water Development Commission and the town of Cokeville, variously paged.

Forsgren Associates, 1993b, in association with Huntingdon Chen-Northern, Inc., and

TriHydro Corporation, Cokeville water supply level II study, supplemental reports: report prepared for the Wyoming Water Development Commission and the town of Cokeville, variously paged.

Forsgren Associates, Inc., 2000, North Uinta County Improvement and Service District water supply master plan level I, final report: prepared for the Wyoming Water Development Commission, variously paged.

Forsgren and Associates 2001, in association with Anderson Consulting Engineers, Inc., Leonard Rice Engineers, Inc., and BBC Research and Consulting, Bear River Basin water plan, final report and technical memoranda: prepared for the Wyoming Water Development Commission, variously paged.

Frank, J.R., Cluff, S., and Bauman, J.M., 1982, Painter Reservoir and East Painter Reservoir, and Clear Creek Fields, Uinta County, Wyoming, in Powers, R.B., editor, Geologic Studies of the Cordilleran Thrust Belt: Rocky Mountain Association of Geologists, Denver, Colorado, p. 601–611.

Furer, L.C., 1967, Sedimentary petrology and regional stratigraphy of the non-marine Upper Jurassic–Lower Cretaceous rocks of western Wyoming and southeastern Idaho: Madison, University of Wisconsin, unpublished Ph.D. dissertation, 175 p.

Furer, L.C., 1970, Petrology and stratigraphy of nonmarine Upper Jurassic–Lower Cretaceous rocks of western Wyoming and southeastern Idaho: American Association of Petroleum Geologists Bulletin, v. 54, no. 12, p. 2282–2302.

Galloway, D.L. and Burbey, T.J., 2011, Review: Regional land subsidence accompanying groundwater extraction: Hydrogeol. J. 19: p 1459–1486.

Geldon, A.L., 2003, Hydrologic properties and ground-water flow systems of the Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin: U.S. Geological Survey Professional Paper 1411–B, 153 p., 13 plates in separate volume.

Geological Survey of Wyoming, 1937, Geologic map of Uinta County, Wyoming: Compiled from all available data by the Geological Survey of Wyoming in cooperation with the Wyoming State Planning Board, Geological Survey of Wyoming, map scale 1:253,440 (1 inch = 4 miles), 1 sheet (rolled).

Gibbons, A.B., and Dickey, D.D., 1983, Quaternary faults in Lincoln and Uinta counties, Wyoming, and Rich County, Utah: U.S. Geological Survey Open-File Report 83-288 (OFR 83-288), map scale 1:100,000, 1 sheet.

Gibbons, A.B., 1986a, Surficial materials map of the Evanston 30' x 60' quadrangle, Uinta and Sweetwater counties, Wyoming: U.S. Geological Survey Coal Map C-103, map scale 1:100,000, 1 sheet.

Gibbons, A.B., 1986b, Surficial materials map of the Kemmerer 30' x 60' quadrangle, Lincoln, Uinta, and Sweetwater counties, Wyoming: U.S. Geological Survey Coal Map C-102, map scale 1:100,000, 1 sheet.

Glover, K.C., 1988, A finite-element model for simulating hydraulic interchange of surface and ground water: U.S. Geological Survey Water-Resources Investigations Report 86–4319, 90 p.

Glover, K.C., 1990, Stream-aquifer system in the Upper Bear River valley, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 89–4173, 58 p.

Glover, K.C., Naftz, D.L., and Martin, L.J., 1998, Geohydrology of Tertiary rocks in the Upper Colorado River Basin in Colorado, Utah, and Wyoming, excluding the San Juan Basin: U.S. Geological Survey Water-Resources Investigations Report 96-4105, 103 p.

Hale, L.A., 1960, Frontier Formation—Coalville, Utah, and nearby areas of Wyoming and Colorado, in McGookey, D.P., and Miller, D.N., Jr., eds., Overthrust Belt of southwestern Wyoming and adjacent areas: Wyoming Geological Association Guidebook, 15th Annual Field Conference, 1960, p. 136–146.

Hamerlinck, J.D., and Arneson, C.S., eds., 1998, Wyoming ground water vulnerability assessment handbook: Volumes 1 and 2, University of Wyoming, Laramie, Spatial Data and Visualization Center Publication SDVC 98-01, variable pagination.

Hansen, W.R., 1969, The geologic story of the Uinta

Mountains: U.S. Geological Survey Bulletin 1291, second printing 1975, 144 p.

Harris, R. E., 1996, Industrial Minerals and construction materials of Wyoming: Wyoming State Geological Survey Map Series 47, Laramie, Wy. 1 plate.

Hausel, W.D., 1989, The geology of Wyoming's precious metal lode and placer deposits: Wyoming State Geological Survey Bulletin 68, 248 p.

Hausel, W.D., 1993, Precious metal, base metal and gemstone deposits in Wyoming: Wyoming State Geological Survey Reprint 54, 28 p.

Hausel, W.D. 1997, Copper, lead, zinc, molybdenum, and other associated metal deposits of Wyoming: Wyoming State Geological Survey Bulletin 70, Laramie, Wy., 229 p.

Hausel, W.D., 2002, Searching for gold in Wyoming, Wyoming State Geological Survey Information Pamphlet 9, Laramie, Wy. 16 p.

Hausel, W. D. and Sutherland, W. M., 2000, Gemstones and other unique rocks and minerals of Wyoming: Wyoming State Geological Survey Bulletin 71, 268 p.

Healy, R. W. and Scanlon, B. R., 2010, Estimating groundwater recharge: Cambridge University Press, 245 p.

Heath, R.C., 1983 (revised 2004), Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 86 p.

Helsel, D.R., and Cohn, T.A., 1988, Estimation of descriptive statistics for multiply censored water quality data: Water Resources Research, v. 24, no. 12, p. 1997–2004.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Amsterdam, Elsevier, 529 p.; and as Techniques of Water-Resource Investigations of the United States Geological Survey, book 4, A3, 510 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water (3d. ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Henderson, Jade, Water Division IV Superintendent, Wyoming State Engineer's Office, Cokeville, WY, 2011. personal communication.

High Plains Regional Climate Center. "CLIMOD." http://climod.unl.edu

Hoffman, M.E., and Balcells-Baldwin, R.N., 1982, Gas giant of the Wyoming Thrust Belt—Whitney Canyon-Carter Creek Field, in Powers, R.B., ed., Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, p. 613–618.

Holm, M.R., 1992, Chicken Creek, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin and Overthrust Belt: Wyoming Geological Association, p. 96–97.

Huntoon, P. W., 1983a, Fault severed aquifers along the perimeters of Wyoming artesian basins: Ground Water, v. 23, no. 2, p. 176-181.

Hurst, D.J., 1984, Depositional environment and tectonic significance of the Tunp Member of the Wasatch Formation, southwest Wyoming: Laramie, University of Wyoming, M.S. thesis, 115 p.

Hurst, D.J., and Steidtmann, J.R., 1986, Stratigraphy and tectonic significance of the Tunp Conglomerate in the Fossil Basin, Southwest Wyoming: Mountain Geologist, v. 23, no. 1, p. 6–13.

Idaho Department of Water Resources, 2012, http://www.idwr.idaho.gov/

Imlay, R.W., 1952, Marine origin of Preuss Sandstone of Idaho, Wyoming, and Utah: American Association of Petroleum Geologists Bulletin, v. 36, no. 9, p. 1735–1753.

Imlay, R.W., 1967, Twin Creek Limestone (Jurassic) in the Western Interior of the United States: U.S. Geological Survey Professional Paper 540, 16 plates, 105 p.

Jarvis, W.T., 1986, Regional hydrogeology of the Paleozoic aquifer system, southeastern Bighorn Basin, Wyoming, with an impact analysis on Hot Springs State Park, Part I: Laramie, University of Wyoming, M.S. thesis, variously paged.

Jenkins, C.T., 1968a, Computation of rate and volume of stream depletion by wells: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chapter Dl, 17 p.

Jenkins, C.T., 1968b, Electric analog and digital computer model analysis of stream depletion by wells: Ground Water, v. 6, no. 6, p. 27–34.

Johnson-Fermelia Company, Inc., 1991, Phase 1

report, Cokeville water supply study project level I: prepared for the Wyoming Water Development Commission, variously paged.

Jones, E.V., Jr., 1979, Painter Reservoir, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin: Wyoming Geological Association, p. 272–273.

Jones, N. R., R. W. Jones and Lucke, D. W., 2011, Coal map of Wyoming: Wyoming State Geological Survey Map Series 93, Laramie, Wy. 1 plate.

Konikow, L.F., 2013, Groundwater depletion in the United States (1900–2008): U.S. Geological Survey Scientific Investigations Report 2013–5079, 63 p., http://pubs.usgs.gov/sir/2013/5079.

Kummel, Bernhard, 1954, Triassic stratigraphy of southeastern Idaho and adjacent areas: U.S. Geological Survey Professional Paper 254–H, A Shorter Contribution to General Geology, p. 165–189.

Lamb, C.F., 1980, Painter Reservoir Field—Giant in Wyoming thrust belt: American Association of Petroleum Geologists Bulletin, v. 64, p. 638–644.

Lee, C. H., 1915, The determination of safe yield of underground reservoirs of the closed basin type: Transactions, American Society of Civil Engineers, v. 78, p. 148–251.

Lindner-Lunsford, J.B., Kimball, B.A., Chafin, D.T., and Bryant, C.G., 1989, Hydrogeology of aquifers of Paleozoic age, Upper Colorado River Basin, excluding the San Juan Basin, in Colorado, Utah, Wyoming, and Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA–702, 2 sheets, scale 1:2,500,000 and 1:5,000,000.

Lines, G.C., and Glass, W.R., 1975, Water resources of the thrust belt of western Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–539, 3 sheets.

Lohman, S. W., Bennett, R. R., Brown, R. H., Cooper, Jr., H. H., Drescher, W. J., Ferris, J. G., Johnson, A. I., McGuinness, C. L., Piper, A. M., Rorabaugh, M. I., Stallman, R. W., and Theis, C. V., 1972, Definitions of selected ground-water terms - revisions and conceptual refinements, U.S. Geological Survey, Water

Supply Paper 1988, 21 p.

Love, J.D., and Christiansen, A.C. (compilers), 1985, Geologic map of Wyoming: U.S. Geological Survey, map scale 1:500,000, 3 sheets.

Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J. (compilers), 1993, Stratigraphic chart showing Phanerozoic nomenclature for the State of Wyoming: Laramie, Geological Survey of Wyoming Map Series MS–41, 1 sheet.

Lowham, H.W., Peterson, D.A., Larson, L.R., Zimmerman, E.A., Ringen, B.H., and Mora, K.L., 1985, Hydrology of Area 52, Rocky Mountain Coal Province, Wyoming, Colorado, Idaho, and Utah: U.S. Geological Survey Water-Resources Investigations/Open-File Report 83-761, Cheyenne, Wyoming, October 1985, 96 p.

Lowry, S., Wyoming State Engineer's Office. 1992. Wyoming's Bear River Basin Base Mapping Project & Estimated Increased Depletions, January 1, 1976 through January 1, 1990. Submitted to the Bear River Commission.

Lynds, R. 2013, Wyoming's Oil and Gas Resources Summary Report: Wyoming State Geological Survey, Laramie, Wy. 4 p.

Maimone, M., 2004, Defining and managing sustainable yield; Ground Water 42, no. 6: p. 809–814.

Mallory, W.W., 1967, Pennsylvanian and associated rocks in Wyoming: U.S. Geological Survey Professional Paper 554–G, 31 p.

Mandel, S., and Shiftan, Z. L., 1981, Ground-water resources— Investigation and development: Academic Press, New York, 269 p.

Martin, L.J., 1996, Geohydrology of Tertiary rocks in the Green River Structural Basin in Wyoming, Utah, and Colo¬rado: U.S. Geological Survey Water-Resources Investigations Report 92–4164, 43 p.

McGarry, D.E., and Hunt, J.D., 1992a, Carter Creek, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin and Overthrust Belt: Wyoming Geological Association, p. 82–87.

McGarry, D.E., and Hunt, J.D., 1992b, Whitney Canyon, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas

Fields Symposium, Greater Green River Basin and Overthrust Belt: Wyoming Geological Association, p. 348–352.

McGuire, V.L., 2013, Water-level and storage changes in the High Plains aquifer, predevelopment to 2011 and 2009–11: U.S. Geological Survey Scientific Investigations Report 2012–5291, 15 p. (Also available at http://pubs.usgs.gov/sir/2012/5291/.)

Meinzer, O. E., 1923, The occurrence of ground water in the United States, with a discussion of principles, Water Supply Paper 489, 321 p.

M'Gonigle, J.W., and Dover, J.H., 1992, Geologic map of the Kemmerer 30' x 60' quadrangle, Lincoln, Uinta, and Sweetwater Counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I–2079, map scale 1:100,000, 1 sheet.

Moklestad, T.C., 1979, Yellow Creek, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin: Wyoming Geological Association, p. 426–427.

MSM Consultants, and Willard Owens Associates, Inc., 1982, Town of Kemmerer, Wyoming groundwater availability study vicinity of Kemmerer, Wyoming: prepared for the Wyoming Water Development Commission, 122 p., 3 pl.

MWH Americas, Inc., 2010, in association with Short Elliott Hendrickson, Inc., and Harvey Economics, Wind-Bighorn Basin Plan Update, Report: prepared for the Wyoming Water Development Commission, variously paged.

Naftz, D.L., 1996, Geochemistry of selected aquifers in Tertiary rocks of the Upper Colorado River Basin in Wyoming, Colorado, and Utah: U.S. Geological Survey Water-Resources Investigations Report 95–4065, 45 p.

Nelson, M.E., 1973, Age and stratigraphic relations of the Fowkes Formation (Eocene) of southwestern Wyoming and northeastern Utah: Contributions to Geology, University of Wyoming, v. 12, no. 1, p. 27–31.

Ogle, K.M., Eddy-Miller, C.A., and Busing, C.J., 1996, Estimated use of water in Lincoln County, Wyoming, 1993: U.S. Geological Survey Water-Resources Investigations Report 96-4162, 13 p.

Oriel, S.S., 1969, Geology of the Fort Hill quadrangle, Lincoln County, Wyoming: U.S. Geological Survey Professional Paper 594–M, 40 p.

Oriel, S.S., and Platt, L.B., 1980, Geologic map of the Preston 1o x 2o quadrangle, Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I–1127, map scale 1:250,000, 1 sheet.

Oriel, S.S., and Tracey, J.I., Jr., 1970, Uppermost Cretaceous and Tertiary stratigraphy of Fossil Basin, southwestern Wyoming: U.S. Geological Survey Professional Paper 635, 53 p.

Piper, A.M., 1944, A graphic procedure in the geochemical interpretation of water analyses: American Geophysical Union Transactions, v. 25, p. 914–923.

Pipiringos, G.N., and Imlay, R.W., 1979, Lithology and subdivisions of the Jurassic Stump Formation in southeastern Idaho and adjoining areas: U.S. Geological Survey Professional Paper 1035–C, Unconformities, correlation, and nomenclature of some Triassic and Jurassic rocks, Western Interior United States, 25 p.

Poland, J. F., Lofgren, B. E., Riley, Francis S., 1972, Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal, USGS Water Supply Paper 2025, 9 p.

Powers, R.B., 1992, Glasscock Hollow, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin and Overthrust Belt: Wyoming Geological Association, p. 156–157.

PRISM Climate Group, 2013 @ http://prism.oregonstate.edu/

Richter, H.R., Jr., 1981, Occurrence and characteristics of ground water in the Wind River Basin, Wyoming: Laramie, University of Wyoming Water Resources Research Institute, volume IV of a series of reports prepared for the U.S. Environmental Protection Agency, variously paged.

RJH Consultants, Inc., 2010, Sublette Creek Reservoir, Mau/Covey Canal Rehabilitation Level II Project, Volume I and II. Wyoming Water Development Commission, Cheyenne, WY.

Robinove, C.J., and Berry, D.W., 1963, Availability of ground water in the Bear River valley,

Wyoming, with a section on Chemical quality of the water, by J.G. Connor: U.S. Geological Survey Water-Supply Paper 1539–V, 44 p., 2 pl.

Robinove, C.J., and Cummings, T.R., 1963, Ground-water resources and geology of the Lyman – Mountain View area, Uinta County, Wyoming: U.S. Geological Survey Water-Supply Paper 1669-E, 1 plate, 43 p.

Royse, F., Jr., 1993, An overview of the geologic structure of the thrust belt in Wyoming, northern Utah, and eastern Idaho: in Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., editors, Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 272-311.

Rubey, W.W., 1973a, Geologic map of the Afton quadrangle and part of the Big Piney quadrangle, Lincoln and Sublette counties, Wyoming: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-686, map scale 1:62,500, 2 sheets.

Rubey, W.W., 1973b, New Cretaceous formations in the western Wyoming thrust belt: U.S. Geological Survey Bulletin 1372–I, p. I1–I135

Rubey, W.W., Oriel, S.S., and Tracey, J.I., Jr., 1961, Age of the Evanston Formation, western Wyoming: U.S. Geological Survey Professional Paper 424-B, Geological Survey Research 1961: Short Papers in the Geologic and Hydrologic Sciences, Article 64, p. B153-B154.

Rubey, W.W., Oriel, S.S., and Tracey, J.I., Jr., 1976, Geologic map of the Cokeville 30-minute quadrangle, Lincoln and Sublette counties, Wyoming: U.S. Geological Survey Open-File Report 76-597 (OFR 76-597), map scale 1:62,500, 1 sheet.

Rubey, W.W., Oriel, S.S., and Tracey, J.I., Jr., 1980, Geologic map and structure sections of the Cokeville 30-minute quadrangle, Lincoln and Sublette Counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I–1129, map scale 1:62,500, 2 sheets.

Salat, T.S., 1989, Provenance, dispersal, and tectonic significance of the Evanston Formation and Sublette Range Conglomerate, Idaho-Wyoming-Utah thrust belt: Laramie, University of Wyoming, M.S. thesis, 100 p.

Salat, T.S., and Steidtmann, J.R., 1991, Provenance,

dispersal, and tectonic significance of the Evanston Formation and Sublette Range Conglomerate, Idaho-Wyoming-Utah thrust belt: Mountain Geologist, v. 28, no. 1, p. 25–36.

Sanford, W. E., and Selnick, D.L., 2013, Estimation of evapotranspiration across the conterminous United States using a regression with climate and land-cover data: Journal of the American Water Resources Association, vol. 49, no. 1, p. 217-230.

Schowalter, T.T., 1979, Stove Creek, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin: Wyoming Geological Association, p. 370–371.

Schroeder, M.L., 1969, Geologic map of the Teton Pass quadrangle, Teton County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ–793, map scale 1:24,000, 1 sheet.

SEO/State Engineer's Office, 2013, @ https://sites.google.com/a/wyo.gov/seo/home

Sercombe, W.J., 1989, Performance of lower-porosity Nugget reservoirs, Anschutz Ranch East, Bessie Bottom, and North Pineview Fields, Utah and Wyoming, in Coalson, E.B., and Kaplan, S.S., eds., Petrogenesis and petrophysics of selected sandstone reservoirs of the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 109–116.

Sharp, J.M. Jr., 2007. A glossary of hydrogeological terms: Department of Geological Sciences, University of Texas, Austin, Texas, 63 p.

Sieverding, J.L., and Royse, Frank, Jr., 1990, Whitney Canyon-Carter Creek Field, U.S.A., western Wyoming thrust belt, in Foster, N.H., and Beaumont, E.A., compilers, Structural traps III—Tectonic fold and fault traps: American Association of Petroleum Geologists Treatise Atlas, p. 1–29.

Smith, M.E., and Maderak, M.L., 1993, Geomorphic and hydraulic assessment of the Bear River in and near Evanston, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 93-4032, 61 p.

Sophocleous, M.A., 1998. On the elusive concept of safe yield and the response of interconnected stream-aquifer systems to development. In: Sophocleous, M.A. (ed.). Perspectives on

Sustainable Development of Water Resources in Kansas. Kansas Geological Survey, Bulletin 239, p. 6-85.

Sophocleous, M.A., 2005, Groundwater recharge and sustainability in the High Plains aquifer in Kansas, USA, Hydrogeology Journal v. 13, no. 2, p. 351–365.

Spencer, S.A., 1986, Groundwater movement in the Paleozoic rocks and impact of petroleum production on water levels in the southwestern Bighorn Basin, Wyoming, Part I: Laramie, University of Wyoming, M.S. thesis, variously paged.

States West Water Resources Corp., 2001, in association with Water Right Services, LLC, 2001 Bear River Basin Water Plan Technical Memorandum Appendix E – Irrigated Lands GIS Data: prepared for the Wyoming Water Development Commission, 8 pp.

Stilwell, D.P., and Chase, J.D., 1992, Session Mountain, in Oil and Gas Field Symposium Committee, eds., Wyoming Oil and Gas Fields Symposium, Greater Green River Basin and Overthrust Belt: Wyoming Geological Association, p. 272–274.

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., and Van Gosen, B.S., 2005, Preliminary integrated geologic map databases for the United States : Central states: Montana, Wyoming, Colorado, New Mexico, Kansas, Oklahoma, Texas, Missouri, Arkansas, and Louisiana: U.S. Geological Survey Open-File Report 2005–1351.

Sunrise Engineering, 1997, Evanston water system master plan level II study: prepared for the Wyoming Water Development Commission, variously paged.

Sunrise Engineering, 2005, in association with Fassett Consulting, LLC., Evanston/Bear River regional pipeline level II study: prepared for the Wyoming Water Development Commission, variously paged.

Taucher, P., Bartos, T.T., Quillinan, S.A., Hallberg, L.L., Clark, M.A., Thompson, M., Gribb, N., Worman, B., and Gracias, T., 2012, Wind/Bighorn River basin water plan update, groundwater study level I (2008 – 2011), available groundwater determination, technical memorandum: prepared by the Wyoming State Geological Survey, United States Geological Survey, Water Resources Data System in cooperation with the Wyoming State Engineer's Office and the Wyoming Oil and Gas Conservation Commission, prepared for the Wyoming Water Development Commission, variously paged.

Taucher, P., Bartos, T.T., Taboga, K.G., Hallberg, L.L, Clark, M.L., Stafford, J., Gracias, T., Hinckley, B., Worman, B., Clarey, K., Lindemann, L., Quillinan, S.A., Copeland, D., Hays, R., and Thompson, M., 2013, Available Groundwater Determination Technical Memorandum, WWDC Platte River Basin Water Plan Update, Level I (2009-2013), Wyoming State Geological Survey, Laramie, Wyoming. 481 p.

Taylor, O.J., Hood, J.W., and Zimmerman, E.A., 1986, Hydrogeologic framework of the Upper Colorado River Basin—excluding the San Juan Basin—Colorado, Utah, Wyoming, and Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA–687, 2 sheets, scale 1:3,000,000.

Theis, C.V., 1940, The source of water derived from wells: Essential factors controlling the response of an aquifer to development, Civil Engineer 10, p. 277 – 280.

Tillman, L.E., 1989, Sedimentary facies and reservoir characteristics of the Nugget Sandstone (Jurassic), Painter Reservoir Field, Uinta County, Wyoming, in Coalson, E.B., and Kaplan, S.S., eds., Petrogenesis and petrophysics of selected sandstone reservoirs of the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 97–108, and plates, p. 316–317.

TriHydro Corporation, 1992, Phase I report: Level II feasibility study, ground-water alternatives investigation, Cokeville, Wyoming: Consultant's report prepared for the WWDC, Cheyenne, Wyoming, and Forsgren Associates, Evanston, Wyoming; prepared for WWDC, various pagination.

TriHydro Corporation, 1993, Phase II report, Well construction and testing program, level II feasibility study, Cokeville, Wyoming, in Forsgren Associates, 1993, in association with Huntingdon Chen-Northern, Inc., and

TriHydro Corporation, Cokeville water supply level II study, supplemental reports: report prepared for the Wyoming Water Development Commission and the Town of Cokeville, variously paged.

TriHydro Corporation, 1995, Level III construction and testing report, Cokeville No. 2 and Cokeville No. 3 municipal water supply wells, Cokeville, Wyoming (draft): prepared for the WWDC and the Town of Cokeville, various pagination.

TriHydro Corporation, 2000, Hydrogeologic report—North Uinta County Improvement and Service District Water Supply Master Plan, Uinta County, Wyoming: report prepared for the North Uinta County Improvement and Service District, Wyoming Water Development Commission, and Forsgren Associates, Inc., variously paged.

TriHydro Corporation, 2002, Delineation report for Cokeville wellhead protection plan, Town of Cokeville, Wyoming: report prepared for the Town of Cokeville, Wyoming, and Forsgren Associates, Inc., Evanston, Wyoming, variously paged.

TriHydro Corporation, 2003, in association with Forsgren Associates, North Uinta water supply project level II feasibility study, Bear River, Wyoming, final report: prepared for the Wyoming Water Development Commission and the North Uinta County Improvement and Service District, variously paged.

U.S. Census Bureau, 2010, http://www.census.gov/#

U.S. Environmental Protection Agency, 1999, 40 CFR Parts 141 and 142, National Primary Drinking Water Regulations, Radon-222, Proposed Rule: Washington, D.C., Federal Register, v. 64, no. 211, p. 59245–59378.

U.S. Environmental Protection Agency, 2012, 2012 Edi¬tion of the drinking water standards and health advisories: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA 822–S–12–001.

U.S. Fish and Wildlife Service, 2013, http://www.fws.gov/

U.S. Geological Survey, 2010, Produced Waters Database: U.S. Geological Survey database, accessed November 22, 2010 at http://energy.cr.usgs.gov/prov/prodwat/

U.S. Geological Survey, 2012, National Water Information System (NWISWeb): U.S. Geological Survey database, accessed May 11, 2011 at http://waterdata.usgs.gov/wy/nwis/qw/

U.S. Geological Survey, 2011, Wyoming groundwater-quality monitoring network, U. S. Geological Survey fact sheet 2011- 3041, 4 p.

University of Wyoming Enhanced Oil Recovery Institute, 2011, produced water database [Microsoft Excel spreadsheet], accessed November 16, 2011 at http://www.uwyo.edu/eori/areas-of-focus/data_generation.html.

Utah Department of Natural Resources. 2010 Forestry, Fire, and State lands, Utah State University and Utah Water Research Laboratory. "Great Salt Lake Information System." http://greatsaltlake.utah.edu

Utah Division of Water Rights, 2012, http://www.waterrights.utah.gov/

Utah Water Research Laboratory, Utah State University. 2011 "Bear River Watershed Description." http://bearriverinfo.org

Veatch, A.C., 1906, Coal and oil in southern Uinta County, Wyoming: U.S. Geological Survey Bulletin 285-F, p. 331-353.

Veatch, A.C., 1907, Geography and geology of a portion of southwestern Wyoming: U.S. Geological Survey Professional Paper 56, 26 plates, 178 p.

Water Resources Data System, University of Wyoming. "Water and Climate Data for the State of Wyoming." http://www.wrds.uwyo.edu

Welder, G.E., 1968, Ground-water reconnaissance of the Green River Basin, southwestern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–290, 2 sheets; accompanying text, 5 p.

Welder, G.E., and McGreevy, L.J., 1966, Ground-water reconnaissance of the Great Divide and Washakie Basins and some adjacent areas, southwestern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–219, 3 sheets; accompanying text, 10 p.

Western Regional Climate Center. "Historical Climate Information." http://www.wrcc.dri.edu

Weston Engineering, Inc., 2008, Douglas ground water level II study, final report: prepared for the

Wyoming Water Development Commission, variously paged.

White, R.R., Alcock, T.J., and Nelson, R.A., 1990, Anschutz Ranch East Field, U.S.A., Utah-Wyoming thrust belt, in Foster, N.H., and Beaumont, E.A., compilers, Structural traps III—Tectonic fold and fault traps: American Association of Petroleum Geologists Treatise Atlas, p. 31–55.

Whitehead, R.H., 1996 Ground water atlas of the United States, Segment 8, Montana, North Dakota, South Dakota, Wyoming: U.S. Geologic Survey Hydrologic Investigations Atlas HA-730-I, 24 p.

WWC Engineering, Inc., 2007, in association with Hinckley Consulting, Collins Planning Associates, Greenwood Mapping, Inc., and States West Water Resources Corporation, Wyoming framework water plan: prepared for the Wyoming Water Development Commission, Cheyenne, Wy., v. 1 and 2, variously paged.

WyGISC, (Wyoming Geographic Information Science Center), 2013, http://www.uwyo.edu/wygisc/

Wyoming Department of Environmental Quality, 1993 (revised 2005) Quality standards for Wyoming groundwaters: Cheyenne, Wyoming Department of Environmental Quality, Chapter VIII, 87 p.

Wyoming Economic Analysis Division, 2008, Populations for Wyoming, Counties, Cities, and Towns: 2000 to 2030: http://eadiv.state.wy.us/

Wyoming Oil and Gas Conservation Commission, 2013, http://wogcc.state.wy.us/

Wyoming State Geological Survey, 2005, Coalbed Natural Gas Conference: I – Research, Monitoring, and Applications: edited by J. R. Stine, Wyoming State Geological Survey Public Information Circular No. 43, 68 p.

Wyoming State Geological Survey (WSGS), 2012, http://www.wsgs.uwyo.edu/ Maps and plates compiled by WSGS (Appendix C).

Wyoming State Engineer's Office, 2012, https://sites.google.com/a/wyo.gov/seo/

Wyoming State Statutes, 2013, http://www.lexisnexis.com/hottopics/wystatutes/

Wyoming Water Development Commission, 2009, Water System Survey Report: Cheyenne, Wyoming. Prepared in Association with the University of Wyoming, Water Resources Data System, Laramie, Wyoming, variously paged.

Wyoming Water Development Office/Commission, 2012, in association with the State Engineer's Office and U.W. Water Resources Data System, 2011 Bear River Basin plan update, final report, technical memoranda, GIS products and hydrologic models: variously paged.

Wyoming. Water Planning Program, 1973, Wyoming's groundwater supplies: Cheyenne, Wyoming State Engineer's Office, Wyoming Water Planning Program Report, variously paged.

Appendix A
Geographic Information System (GIS)

This appendix describes the 53 digital Geographic Information System (GIS) geologic units that comprise the Bear River Basin (BRB) of Wyoming, Utah, and Idaho. The stratigraphic descriptions in this appendix are for the units shown on Plate I. The 53 digital GIS geologic units are distributed as follows:

Wyoming   28 geologic units   page   A1-11
Utah   21 geologic units   page   A11-14
Idaho   4 geologic units   page   A1-11

These geologic units are compiled from the 1:500,000-scale digital state maps that cover the BRB. The maps give a code and rock-type description to each unit within the mapped state; each state has its own set of codes, and neither codes nor unit boundaries necessarily match across state lines.

In this appendix, for each state, each geologic unit symbol (**bold face**) and GIS definition (<u>underlined</u>) is followed by a description of the corresponding stratigraphic unit(s) as defined in that state. **Plate 1** summarizes these determinations. Rock-stratigraphic units that appear in the right-hand column of **Plate 1** are in **boldface**.

BEAR RIVER BASIN GEOLOGIC UNITS – WYOMING

There are 28 digital GIS geologic units in the Wyoming portion of the Bear River Basin (Love and Christiansen, 1985). The stratigraphic descriptions below are taken directly from Love and Christiansen (1985) with minor modifications. Unit labels for Utah and Idaho can be found at the end of the unit description for correlative units.

References
Love, J.D., and Christiansen, A.C., *compilers*, 1985, Geologic map of Wyoming: U.S. Geological Survey, scale 1:500,000, 3 sheets.
Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., *compilers*, 1993, Stratigraphic chart showing the Phanerozoic nomenclature for the state of Wyoming: Geological Survey of Wyoming Map Series 41 (MS-41).

<u>Symbol   Unit Description</u>

CENOZOIC GEOLOGIC UNITS – WYOMING

Quaternary geologic units – Wyoming, Utah, and Idaho

Qa   <u>Alluvium and colluvium</u> (Holocene-Pleistocene) – Clay, silt, sand, and gravel in flood plains, fans, terraces, and slopes. Idaho - **Qa**

Qg   <u>Glacial deposits</u> (Holocene-Pleistocene) – Till and outwash of sand, gravel, and boulders.

Qls   <u>Landslide deposits</u> (Holocene-Pleistocene) – Local intermixed landslide and glacial deposits, talus, and rock-glacier deposits.

Qt   <u>Gravel, pediment, and fan deposits</u> (Holocene-Pleistocene) – Mostly locally derived clasts; locally includes some Tertiary gravels.

Symbol   Unit Description

Qu   Undivided surficial deposits (Holocene-Pleistocene) – Mostly alluvium, colluvium, and glacial and landslide deposits.

Quaternary and Tertiary geologic units – Wyoming, Utah, and Idaho

QTg   Terrace gravel (Pleistocene and (or) Pliocene) – Partly consolidated gravel above and flanking some major streams. Utah - Qao

Tertiary geologic units – Wyoming, Utah, and Idaho

Tsl   Salt Lake Formation (Pliocene and Miocene) – White, gray, and green limy tuff, siltstone, sandstone, and conglomerate. Utah – T4, Idaho - Ted

Tbi   Bishop Conglomerate (Oligocene) – Clasts of red quartzite, gray chert, and limestone in a gray to white tuffaceous sandstone matrix.

Tf   Fowkes Formation (Pliocene(?) and Eocene) – Light-colored tuffaceous sandstone and siltstone, locally conglomeratic. Locally designated by some as Norwood Tuff. Utah – T2

Tgrw   Green River and Wasatch Formations (Eocene)
              Green River Formation – Buff laminated marlstone and limestone, brown oil shale, and
              siltstone, includes Angelo and Fossil Butte Members.
              Wasatch Formation – Variegated mudstone and sandstone. Includes Tunp and Bullpen
              Members, other tongues and unnamed members, and main body.

Twd   Wasatch Formation (Diamictite and sandstone) (Eocene) – Diamictite grades laterally into other members of the formation

Tw   Wasatch Formation (main body) (Eocene) – Thrust Belt – Variegated red to gray, brown, and gray mudstone and sandstone; conglomeratic lenses.
              Southwest Wyoming – Drab to variegated claystone and siltstone, carbonaceous shale and coal, buff sandstone, arkose, and conglomerate. Utah – T1

Tcs   Conglomerate of Sublette Range (Eocene and Paleocene) – Locally derived indurated angular conglomerate.

Tertiary and Cretaceous geologic units – Wyoming, Utah, and Idaho

TKe   Evanston Formation (Paleocene and Upper Cretaceous) – Gray siltstone, sparse red sandstone, and lignite beds.

Cretaceous geologic units – Wyoming, Utah, and Idaho

Kav   Adaville Formation (Upper Cretaceous) – Gray sandstone, siltstone, and carbonaceous claystone; conglomeratic in upper part; coal-bearing in lower part.

Kh   <u>Hillard Shale</u> (Upper Cretaceous) – Dark gray to tan claystone, siltstone, and sandy shale.

Kf   <u>Frontier Formation</u> (Upper Cretaceous) – White to brown sandstone and dark-gray shale; oyster coquina in upper part; coal and lignite in lower part. Utah – **K2**

Kss   <u>Sage Junction, Quealy, Cokeville, Thomas Fork, and Smiths Formations</u> (Lower Cretaceous)
<u>Sage Junction Formation</u> – Gray and tan siltstone and sandstone.
<u>Quealy Formation</u> – Variegated mudstone and tan sandstone.
<u>Cokeville Formation</u> – Tan sandstone, claystone, limestone, bentonite, and coal.
<u>Thomas Fork Formation</u> – Variegated mudstone and gray sandstone.
<u>Smiths Formation</u> – Ferruginous black shale and tan to brown sandstone.

Ka   <u>Aspen Shale</u> (Lower Cretaceous) – Light to dark-gray siliceous tuffaceous shale and siltstone, thin bentonite beds, and quartzitic sandstone. Utah – **K1**

Kg   <u>Gannett Group</u> (Lower Cretaceous) – Red sandy mudstone, sandstone, and chert-pebble conglomerate; thin limestone and dark-gray shale in upper part, more conglomeratic in lower part. Includes Smoot Formation (red mudstone and siltstone), Draney Limestone, Bechler Conglomerate, Peterson Limestone, and Ephraim Conglomerate. Upper Jurassic fossils have been reported from the Ephraim. Idaho - **Kl**

Jurassic geologic units – Wyoming, Utah, and Idaho

Jst   <u>Stump Formation, Preuss Sandstone or Redbeds, and Twin Creek Limestone</u> (Upper and Middle Jurassic) Utah **- J1, Idaho - Ju**
<u>Stump Formation</u> – Glauconitic siltstone, sandstone, and limestone.
<u>Preuss Sandstone or Redbeds</u> – Purple, maroon, and reddish-gray sandy siltstone and claystone; contains salt and gypsum in thick beds in some subsurface sections.
<u>Twin Creek Limestone</u> – Greenish-gray shaly limestone and limy siltstone. Includes Gypsum Spring Member.

Jurassic and Triassic geologic units – Wyoming, Utah

JŦn   <u>Nugget Sandstone</u> (Jurassic and Triassic) – Buff to pink crossbedded well-sized and well-sorted quartz sandstone and quartzite; locally has oil and copper-silver-zinc mineralization.

Triassic geologic units – Wyoming, Utah, and Idaho

Ŧad   <u>Ankareh Formation, Thaynes Limestone, Woodside Shale, and Dinwoody Formation</u> (Upper and Lower Triassic) Utah – **Tr1**
<u>Ankareh Formation</u> – Red and maroon shale and purple limestone.
<u>Thaynes Limestone</u> – Gray limestone and limy siltstone.
<u>Woodside Shale</u> – Red siltstone and shale.
<u>Dinwoody Formation</u> – Gray to olive-drab dolomitic siltstone.

Symbol   Unit Description

Permian geologic units – Wyoming, Utah

Pp   Phosphoria Formation (Permian) – Upper part is dark- to light-gray chert and shale with black
         shale and phosphorite at top; lower part is black shale, phosphorite, and cherty dolomite. Utah –
         P2

Permian, Pennsylvanian, and Mississippian geologic units – Wyoming, Utah

PlPMa   Phosphoria, Wells, and Amsden Formations (Permian-Upper Pennsylvainian) Utah - PP
                  Phosphoria Formation (Permian) – Upper part is dark- to light-gray chert and shale with
                  black shale and phosphorite at top; lower part is black shale, phosphorite, and cherty
                  dolomite.
                  Wells Formation – Gray limestone interbedded with yellow limy sandstone.
                  Amsden Formation – Red and gray cherty limestone and shale, sandstone, and
                  conglomerate.

PlPM   Wells and Amsden Formations (lower Permian-Upper Mississippian)
                  Wells Formation – Gray limestone interbedded with yellow limy sandstone.
                  Amsden Formation – Red and gray cherty limestone and shale, sandstone, and
                  conglomerate.

Pennsylvanian geologic units – Wyoming, Utah

Pzr   Paleozoic rocks (undifferentiated) – May include Madison Limestone, Darby Formation, and
Bighorn Dolomite. Utah - P

Mississippian and Devonian geologic units – Wyoming, Utah

MD   Madison Group and Darby Formation (Upper Mississippian-Upper Devonian) Utah –

M2   Madison Limestone or Group – Group includes Mission Canyon Limestone (blue-gray,
                  massive limestone and dolomite), underlain by Lodgepole Limestone (gray cherty
limestone and dolomite).
                  Darby Formation – Yellow and greenish-gray shale and dolomitic siltstone underlain by
                  fetid brown dolomite.

         Uncorrelated Utah geologic units – **M1**, Gardison/Lodgepole Limestone, **D**, Beirdneau Sand-
         stone, Hyrum Dolomite, and Water Canyon Formation

Silurian geologic units – Wyoming, Utah

Sl   Laketown Dolomite (Upper and Middle Silurian) – Light-gray thick-bedded finely crystalline
dolomite. Utah - S

Ordovician and Cambrian geologic units – Wyoming, Utah

OꞒ   Bighorn Dolomite, Gallatin Limestone, and Gros Ventre Formation (Upper Ordovician-Middle Cambrian) Utah **-** O

> Bighorn Dolomite – Gray massive cliff-forming siliceous dolomite and locally dolomitic limestone.
> Gallatin Limestone – Gray and tan limestone.
> Gros Ventre Formation – Greenish-gray micaceous shale.

> Uncorrelated Utah geologic units: **C3** - St Charles Formation, Nounan Dolomite, and Bloomington Formation, **C2** – Maxfield Limestone and Ophir Formation, **C1** – Tintic Quartzite

Precambrian geologic units – Utah

> Uncorrelated Utah geologic units: **PCs** – Mutual Formation, Mineral Fork Tillite, and Big Cottonwood Formation.

Appendix B

WWDC Groundwater Studies

Citation(s)	Location	Aquifer/Formation	Project Description	Results/Recommendations	Current Status
Wyoming River Basins					
Wyoming. Water Planning Program, 1973, Wyoming's groundwater supplies: Cheyenne, Wyoming State Engineer's Office, Wyoming Water Planning Program Report, variously paged.	Wyoming	All	Summary of available groundwater and groundwater sources.	Predictions of aquifer water quantity throughout the state of Wyoming.	N/A
WWC Engineering, Inc., 2007a, in association with Hinckley Consulting, Collins Planning Associates, Greenwood Mapping, Inc., and States West Water Resources Corporation, Wyoming framework water plan: prepared for the Wyoming Water Development Commission, Cheyenne, Wy., v. 1 and 2, variously paged.					
Bear River Basin					
Forsgren and Associates 2001, in association with Anderson Consulting Engineers, Inc., Leonard Rice Engineers, Inc., and BBC Research and Consulting, Bear River Basin water plan, final report and technical memoranda: prepared for the Wyoming Water Development Commission, variously paged.	Bear River Basin	All	Develop basin plans with participation from local interest groups that provide defensible hydrologic data to quantify surface and ground water uses.	Current surface and ground water uses, water quality, future demand projects and future water use opportunities quantified and discussed. Continue with planning process with updates every five years.	River basin water planning process continues.
Wyoming Water Development Commission, 2012, in association with the State Engineer's Office and U.W. Water Resources Data System, 2011 Bear River Basin plan update, final report, technical memoranda, GIS products and hydrologic models: variously paged.					
Town of Bear River (see Northern Uinta County below)					
Sunrise Engineering, 2005, in association with Fassett Consulting, LLC, Evanston/Bear River regional pipeline level II study: prepared for the Wyoming Water Development Commission, variously paged.	Town of Bear River, Uinta County		Analyses of water rights, infrastructure, regional water supply system facilities and economics. Provide conceptual design and cost estimates and environmental report.	Proposed PWS is capable of serving Town of Bear River and unincorporated areas between Bear River and Evanston. Project will entail significant funding.	

Citation(s)	Location	Aquifer/Formation	Project Description	Results/Recommendations	Current Status
Cokeville Johnson-Fermelia Company, Inc., 1991, Phase 1 Report, Cokeville water supply study project level I: prepared for the Wyoming Water Development Commission, variously paged, 6 pl	Town of Cokeville, Lincoln County	Gannett, Smith's Fork, Thomas Fork	Assess the adequacy of the supply springs, and water facilities to meet Cokeville's water supply requirements. Investigate water facilities compliance with SDWA.	Supply springs can meet average daily water supply demands, water facilities require improvements, and source water is not under direct influence of surface water.	N/A
Forsgren Associates, 1993a, Cokeville water supply level II study, final report: prepared for the Wyoming Water Development Commission and the Town of Cokeville, Wyoming, variously paged Forsgren Associates, 1993b, in association with Chen Northern, Inc., Trihydro Corporation, Cokeville Water Supply Level II Study, Supplemental Reports, Final Report: prepared for the Wyoming Water Development Commission and the Town of Cokeville, Wyoming, variously paged	Lincoln County	Gannett, Smith's Fork, Thomas Fork	Evaluate existing water system components, water supply needs and alternatives. Complete 3 test wells. Generate conceptual designs and cost estimates for system improvements	Replace springs with shallow well. Modify delivery system. Institute water conservation program. Obtain Level III funding for Cokeville Test well No. 1 near Cokeville /Kenyon Springs.	N/A
Evanston Sunrise Engineering, 1997, Evanston water system master plan level II study: prepared for the Wyoming Water Development Commission, variously paged.	City of Evanston	Bear River Alluvium	Evaluate existing water supply and system facilities, water supply needs and alternatives for the City of Evanston.	City's groundwater wells reserved for emergency use, surface water meets supply requirements. Institute regular maintenance program for water infrastructure. Explore development of raw water irrigation system.	

213

Citation(s)	Location	Aquifer/Formation	Project Description	Results/Recommendations	Current Status
Northern Uinta County					
Forsgren Associates, 2000, North Uinta County Improvement and Service District water supply master plan level I, final report: prepared for the Wyoming Water Development Commission, variously paged.	Northern Uinta County	Bear River alluvium, Fowkes, Wasatch, Evanston and Bear River formations	Level I study to "examine the feasibility and costs to expand the water system in the area of North Uinta County I&S District.	Construct test well at Deer Mountain subdivision, continue regional PWS investigation, seek funding, negotiate water service agreement with City of Evanston.	
TriHydro Corporation, 2000, in association with Forsgren Associates, Hydrogeologic report, North Uinta County Improvement and Service District water supply master plan: prepared for the Wyoming Water Development Commission and the North Uinta County Improvement and Service District, variously paged.					
TriHydro Corporation, 2003, in association with Forsgren Associates, North Uinta water supply project level II feasibility study, Bear River, Wyoming, final report: prepared for the Wyoming Water Development Commission and the North Uinta County Improvement and Service District, variously paged.			Level II status report to evaluate the hydrogeology of aquifer, determine depth to groundwater and aquifer thickness, complete and test new test well, and assess groundwater quality.	Deer Mountain #6 test well in Wasatch formation was completed, developed and tested for aquifer hydraulics and water quality. Level III design and construction should proceed to connect Deer Mountain #6 test well to PWS.	
Current WWDC Bear River Basin Projects					
Bear River Basin Groundwater Analysis WSGS Bear River Hydrology Model WWDC					
Black & Veatch, 1983, Water Supply Needs Assessment for the North Platte and Little Snake River Drainages Phase I, Vols. 1,2: prepared for the Wyoming Water Development Commission, variously paged.	North Platte and Little Snake River Drainages	N/A	Phase I, Volumes I & II, analysis of the water supply needs of various communities located within the North Platte and Little Snake River Conservation District.	There is the possibility to develop enough water to meet both in basin and out of basin needs for the near future	Continue with Phase II of the Water Supply Needs Analysis.

Appendix C

Dataset Sources for Figures and Plates

Dataset	Presented in	Source
GEOLOGY		
		Modified from Vuke, Porter, et al., 2007 Love, J.D.,
Bear River Basin geology	Plate 1, various figures	Christiansen, A.C., 1985
Precambrian basement structure		
contour	Plate 1	Modified from Blackstone, 1993
Precambrian basement faults	Plate 1	Modified from Blackstone, 1993
BRB cross-section lines	Plate 1	WSGS
BRB Lineaments	Plate 1	Cooley, M. E., 1986
		Vuke, Porter, et al., 2007 Love, J.D., Christiansen, A.C.,
BRB faults, Wyoming	Plate 1	1985
		Vuke, Porter, et al., 2007 Love, J.D., Christiansen, A.C.,
BRB faults, Utah	Plate 1	1985
Hydrogeology (includes aquifer out-	Plate 2, Figures 6-1,	
crop areas)	6-2, 6-3, 6-4	T. Bartos, USGS, 2013
Thrust Sheets	Figure 4-1	Modified from Royse, F., Jr., 1993
GROUNDWATER		
Aquifer recharge as a percent of pre-		Modified from Hamerlinck and Arneson, 1998, and
cipitation	Figure 6-5	Daly and Taylor, 1998
Aquifer sensitivity	Figure 5-3	Hamerlinck and Arneson, 1998
Average annual precipitation, 1981-		
2010	Figure 3-3	PRISM Climate Group, Oregon State University
		USGS, Environmental water sample locations GIS
Environmental water sample locations		dataset of 2010
Estimated net annual aquifer recharge	Figure 5-2	Hamerlinck and Arneson, 1998
Produced water sample locations		WOGCC, Produced water database, 2009
Springs		Stafford and Gracias, WSGS, 2009
SWAP locations	Figure 5-11	Modified from Trihydro Corporation, 2004
WWDC potential groundwater devel-		
opment areas		Digitized from BRS, Inc., 2003e
		Wyoming State Engineer's Office, 2012 Idaho De-
	Figures 8-1, 8-2, 8-3,	partment of Water Resources, 2012, Utah Division of
Permited wells	8-4, 8-5, 8-6	Water Rights, 2012

Dataset	Presented in	Source
POTENTIAL GROUNDWATER CONTAMINANTS		
Abandoned mine sites	Figure 5-7	Created from WDEQ Abandoned Mine Land table of 2010
Active coal mine	Figure 5-8	WDEQ, Land Quality Division, 2012
Active disposal and injection wells	Figure 5-4	Modified from WOGCC well header data as of 2009
Small, Limited, and Regular Mining Permits	Figure 5-8	WDEQ LQD, 2012
Non Coal Mines	Figure 5-8	WDEQ LQD, 2011
Storage tanks	Figure 5-10	Modified from WDEQ Solid and Hazardous Waste Division (SHWD) storage tank table of 2009
Active Wyoming Pollutant Discharge Elimination System (WYPDES) outfalls	Figure 5-6	WDEQ Water Quality Division (WQD) WYPDES GIS dataset of 2009
Commercial oil and gas disposal pits	Figure 5-6	WDEQ/WQD commercial oil and gas disposal pit GIS dataset of 2012
Pollution Control Facilities	Figure 5-6	WDEQ/WQD Groundwater Program known contaminated areas GIS dataset of 2012
Oil and gas fields	Figure 5-4	De Bruin, 2007
Pipelines	Figure 5-4	Wyoming Pipeline Authority
Solid and hazardous waste facilities	Figure 5-10	Modified from WDEQ SHWD solid and hazardous waste facilities table of 2009
Underground Injection Control (UIC) Class I and V wells	Figure 5-5	Modified from WDEQ/WQD UIC GIS dataset of 2009
Voluntary Remediation Program (VRP) sites	Figure 5-10	Modified from WDEQ SHWD VRP tables and GIS datasets of 2009
WSGS mines, pits, mills, and plants	Figure 5-9	Harris, 2004
BASE DATA		
Basin boundary	Plate 1, various figures	Modified from USGS National Hydrography Dataset hydrologic units
Elevation	Plate 1, various figures	Modified from U.S. Geological Survey, 1999
Hillshade	Plate 1, various figures	USGS, 1999
Lakes	Plate 1, various figures	USGS, National Hydrologic Dataset
Rivers	Plate 1, various figures	USGS, National Hydrologic Dataset
Wyoming state boundary	Plate 1, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010

Dataset	Presented in	Source
Utah state boundary	Plate 1, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Idaho state boundary	Plate 1, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Wyoming counties	Plate 1, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Utah counties	Plate 1, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Idaho counties	Plate 1, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Wyoming townships	Plate 1, various figures	Premier Data Services, 2008
Utah townships	Plate 1, various figures	Premier Data Services, 2009
Idaho townships	Plate 1, various figures	Bureau of Land Management
Mountain peaks	Physiographic features figure	WSGS, unplublished mountain peaks GIS dataset of 2008
Wyoming roads	Plate 1, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Utah roads	Plate 1, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
Idaho roads	Plate 1, various figures	U.S. Department of Commerce, U.S. Census Bureau, Geography Division, 2010
BRB Towns	Plate 1, various figures	NAUS, 2003

Appendix D
Amended Bear River Compact, 1978

AMENDED BEAR RIVER COMPACT, 1978

Signatory States: Idaho, Utah and Wyoming

Rivers Controlled: Bear River and its tributaries

Ratifications;   Wyo. Stat. Ann. §41-12-101 (2005) [Act of March 6, 1979, 1979 Wyo. Sess.
                         Laws, ch.151, p. 337]
                         Idaho Code §42-3402 (2003) [Act of April 5, 1979, 1979 Idaho Sess. Laws,
                         ch. 322, p. 862]
                         Utah Code Ann. §73-16-2 (2005) [Act of May 8, 1979, 1979 Utah Laws,
                         ch.254, p. 1213]

Summary: The Compact becomes operative only when an emergency is found to exist
                         as provided for by the terms of the Compact. When an emergency is de-
                         clared, the Compact regulates the river by creating three divisions: Upper,
                         Central, and Lower. Water administration becomes effective to diversions by
                         section in the Upper Division; by percentage between the States of Wyoming
                         and Idaho in the Central Division; and by priority for rights in the Lower Divi-
                         sion.
                         The Compact also apportions storage rights in the Bear River Basin above
                         Stewart Dam and allocates increases in depletion from the Bear River and
                         its tributaries, including ground water tributary to the Bear River, which occur
                         on or after January 1, 1976, among the states. Each state is allowed the use
                         of water, including ground water, for ordinary domestic and stock watering
                         purposes including the right to impound water for such purposes in reservoirs
                         having capacities not in excess of 20 acre-feet without deduction from the al-
                         location made in the Compact.

        The State of Idaho, the State of Utah, and the State of Wyoming, acting through their respective
commissioners after negotiations participated in by a representative of the United States of America
appointed by the president, have agreed to an amended Bear River Compact as follows:

ARTICLE I

    A. The major purposes of this compact are to remove the causes of present and future controversy
        over the distribution and use of the waters of the Bear River; to provide for efficient use of water
        for multiple purposes; to permit additional development of the water resources of Bear River; to
        promote interstate comity; to accomplish an equitable apportionment of the waters of the Bear

River among the compacting states.

B. The physical and all other conditions peculiar to the Bear River constitute the basis for this compact. No general principle or precedent with respect to any other interstate stream is intended to be established.

ARTICLE II

As used in this compact the term -

1. "Bear River" means the Bear River and its tributaries from its source in the Uinta Mountains to its mouth in Great Salt Lake

2. "Bear Lake" means Bear Lake and Mud Lake

3. "Upper Division" means the portion of Bear River from its source in the Uinta Mountains to and including Pixley Dam, a diversion dam in the southeast quarter of Section 25, Township 23 North, Range 120 West, Sixth Principal Meridian, Wyoming;

4. "Central Division" means the portion of the Bear River from Pixley Dam to and including Stewart Dam, a diversion dam in Section 34, Township 13 South, Range 44 East, Boise Base and Meridian, Idaho;

5. "Lower Division," means the portion of the Bear River between Stewart Dam and Great Salt Lake, including Bear Lake and its tributary drainage

6. "Upper Utah Section Diversions" means the sum of all diversions in second-feet from the Bear River and the tributaries of Bear River joining the Bear River upstream from the point where the Bear River crosses the Utah-Wyoming state line above Evanston, Wyoming, excluding the diversions by the Hilliard East Fork Canal, Lannon Canal, Lone Mountain Ditch, and Hilliard West Side Canal;

7. "Upper Wyoming Section Diversions" means the sum of all diversions in second-feet from the Bear River main stem from the point where the Bear River crosses the Utah-Wyoming state line above Evanston, Wyoming, to the point where the Bear River crosses the Wyoming-Utah state line east of Woodruff, Utah, and including the diversions by the Hilliard East Fork Canal, Lannon Canal, Lone Mountain Ditch, and Hilliard West Side Canal;

8. "Lower Utah section diversions" means the sum of all diversions in second-feet from the Bear River main stem from the point where the Bear River crosses the Wyoming-Utah state line east of Woodruff, Utah, to the point where the Bear River crosses the Utah-Wyoming state line northeast of Randolph, Utah;

9. "Lower Wyoming Section Diversions" means the sum of all diversions in second-feet from the Bear River main stem from the point where the Bear River crosses the Utah-Wyoming state line northeast of Randolph to and including the diversion at Pixley Dam;

10. "Commission" means the Bear River Commission, organized pursuant to Article III of this Compact;

11. "Water user" means a person, corporation, or other entity having a right to divert water from the Bear River for beneficial use

12. "Second-foot" means a flow of one cubic foot of water per second of time passing a given point

13. "Acre-foot" means the quantity of water required to cover one acre to a depth of one foot, equivalent to 43,560 cubic feet

14. "Biennium" means the 2-year period commencing on October 1 of the first odd numbered year after the effective date of this compact and each 2-year period thereafter;

15. "Water year," means the period beginning October 1 and ending September 30 of the following year

16. "Direct flow" means all water flowing in a natural watercourse except water released from storage or imported from a source other than the Bear River watershed

17. "Border Gaging Station" means the stream flow gauging station in Idaho on the Bear River above Thomas Fork near the Wyoming-Idaho boundary line in the northeast quarter of the northeast quarter of Section 15, Township 14 South, Range 46 East, Boise Base and Meridian, Idaho;

18. "Smiths Fork" means a Bear River tributary, which rises in Lincoln County, Wyoming and flows in a general southwesterly direction to its confluence with Bear River near Cokeville, Wyoming

19. "Grade Creek" means a Smiths Fork tributary that rises in Lincoln County, Wyoming and flows in a westerly direction and in its natural channel is tributary to Smiths Fork in Section 17, Township 25 North, Range 118 West, Sixth Principal Meridian, Wyoming;

20. "Pine Creek" means a Smiths Fork tributary which rises in Lincoln County, Wyoming, emerging from its mountain canyon in Section 34, Township 25 North, Range 118 West, Sixth Principal Meridian, Wyoming, and in its natural channel is tributary to Smiths Fork in Section 36, Township 25 North, Range 119 West, Sixth Principal Meridian, Wyoming;

21. "Bruner Creek" and "Pine Creek Springs" means Smiths Fork tributaries which rise in Lincoln County, Wyoming, in Sections 31 and 32, Township 25 North, Range 118 West, Sixth Principal Meridian, and in their natural channels are tributary to Smiths Fork in Section 36, Township 25 North, Range 119 West, Sixth Principal Meridian, Wyoming;

22. "Spring Creek" means a Smiths Fork tributary which rises in Lincoln County, Wyoming, in Sections 1 and 2, Township 24 North, Range 119 West, Sixth Principal Meridian, Wyoming, and flows in a general westerly direction to its confluence with Smiths Fork in Section 4, Township 24 North, Range 119 West, Sixth Principal Meridian, Wyoming;

23. "Sublette Creek" means the Bear River tributary, which rises in Lincoln County, Wyoming and flows in a general westerly direction to its confluence with Bear River in Section 20, Township 24 North, Range 119 West, Sixth Principal Meridian, Wyoming;

24. "Hobble Creek" means the Smiths Fork tributary, which rises in Lincoln County, Wyoming and flows in a general southwesterly direction to its confluence with Smiths Fork in Section 35, Township 28 North, Range 118 West, Sixth Principal Meridian, Wyoming;

25. "Hilliard East Fork Canal" means that irrigation canal which diverts water from the right bank of the East Fork of Bear River in Summit County, Utah, at a point west 1,310 feet and north 330 feet from the southeast corner of Section 16, Township 2 North, Range 10 East, Salt Lake Base and Meridian, Utah, and runs in a northerly direction crossing the Utah-Wyoming state line into the southwest quarter of Section 21, Township 12 North, Range 119 West, Sixth Principal Meridian, Wyoming;

26. "Lannon Canal" means that irrigation canal which diverts water from the right bank of the Bear River in Summit County, Utah, east 1,480 feet from the west quarter corner of Section 19, Township 3 North, Range 10 East, Salt Lake Base and Meridian, Utah, and runs in a northerly direction crossing the Utah-Wyoming state line into the south half of Section 20, Township 12 North, Range 119 West, Sixth Principal Meridian, Wyoming;

27. "Lone Mountain Ditch" means that irrigation canal which diverts water from the right bank of the

Bear River in Summit County, Utah, north 1,535 feet and east 1,120 feet from the west quarter corner of Section 19, Township 3 North, Range 10 East, Salt Lake Base and Meridian, Utah, and runs in a northerly direction crossing the Utah-Wyoming state line into the south half of Section 20, Township 12 North, Range 119 West, Sixth Principal Meridian, Wyoming;

28. "Hilliard West Side Canal" means that irrigation canal which diverts water from the right bank of the Bear River in Summit County, Utah, at a point north 2,190 feet and east 1,450 feet from the south quarter corner of Section 13, Township 3 North, Range 9 East, Salt Lake Base and Meridian, Utah, and runs in a northerly direction crossing the Utah-Wyoming state line into the south half of Section 20, Township 12 North, Range 119 West, Sixth Principal Meridian, Wyoming;

29. "Francis Lee Canal" means that irrigation canal which diverts water from the left bank of the Bear River in Uinta County, Wyoming, in the northeast quarter of Section 30, Township 18 North, Range 120 West, Sixth Principal Meridian, Wyoming, and runs in a westerly direction across the Wyoming-Utah state line into Section 16, Township 9 North, Range 8 East, Salt Lake Base and Meridian, Utah;

30. "Chapman Canal" means that irrigation canal which diverts water from the left bank of the Bear River in Uinta County, Wyoming, in the northeast quarter of Section 36, Township 16 North, Range 121 West, Sixth Principal Meridian, Wyoming, and runs in a northerly direction crossing over the low divide into the Saleratus drainage basin near the southeast corner of Section 36, Township 17 North, Range 121 West, Sixth Principal Meridian, Wyoming and then in a general westerly direction crossing the Wyoming-Utah state line;

31. "Neponset Reservoir" means that reservoir located principally in Sections 34 and 35, Township 8 North, Range 7 East, Salt Lake Base and Meridian, Utah, having a capacity of 6,900 acre-feet.

ARTICLE III

A. There is hereby created an interstate administrative agency to be known as the "Bear River Commission" which is hereby constituted a legal entity and in such name shall exercise the powers hereinafter specified. The commission shall be composed of nine commissioners, three commissioners representing each signatory state, and if appointed by the president, one additional commissioner representing the United States of America who shall serve as chairman, without vote. Each commissioner, except the chairman, shall have one vote. The state commissioners shall be selected in accordance with state law. Six commissioners who shall include two commissioners from each state shall constitute a quorum. The vote of at least two-thirds of the commissioners when a quorum is present shall be necessary for the action of the commission.

B. The compensation and expenses of each commissioner and each adviser shall be paid by the government which he represents. All expenses incurred by the commission in the administration of this compact, except those paid by the United States of America, shall be paid by the signatory states on an equal basis.

C. The Commission shall have power to:

1. Adopt by-laws, rules, and regulations not inconsistent with this compact;

2. Acquire, hold, convey or otherwise dispose of property;

3. Employ such persons and contract for such services as may be necessary to carry out its

duties under this compact;

4. Sue and be sued as a legal entity in any court of record of a signatory state, and in any court of the United States having jurisdiction of such action;

5. Cooperate with state and federal agencies in matters relating to water pollution of interstate significance;

6. Perform all functions required of it by this compact and do all things necessary, proper or convenient in the performance of its duties hereunder, independently or in cooperation with others, including state and federal agencies.

D. The commission shall:

1. Enforce this compact and its orders made hereunder by suit or other appropriate action

2. Compile a report covering the work of the commission and expenditures during the curreb-biennium, and an estimate of expenditures for the following biennium and transmit it to the President of the United States and to the Governors of the signatory states on or before July 1 following each biennium.

ARTICLE IV

Rights to direct flow water shall be administered in each signatory state under state law, with the following limitations:

A. When there is a water emergency, as hereinafter defined for each division, water shall be distributed therein as provided below.

1. Upper Division

a. When the divertible flow as defined below for the Upper Division is less than 1,250 second-feet, a water emergency shall be deemed to exist therein and such divertible flow is allocated for diversion in the river sections of the Division as follows:

Upper Utah Section Diversions - 0.6 percent, Upper Wyoming Section Diversions - 49.3 pecent, Lower Utah Section Diversions - 40.5 percent, Lower Wyoming Section Diversions - 9.6 percent.

Such divertible flow shall be the total of the following five items:

(1) Upper Utah Section Diversions in second-feet,

(2) Upper Wyoming Section Diversions in second-feet,

(3) Lower Utah Section Diversions in second-feet,

(4) Lower Wyoming Section Diversions in second-feet,

(5) The flow in second-feet passing Pixley Dam.

b. The Hilliard East Fork Canal, Lannon Canal, Lone Mountain Ditch, and Hilliard West Side Canal, which divert water in Utah to irrigate lands in Wyoming, shall be supplied from the divertible flow allocated to the Upper Wyoming Section Diversions.

c. The Chapman, Bear River, and Francis Lee Canals, which divert water from the main stem of Bear River in Wyoming to irrigate lands in both Wyoming and Utah, shall be supplied from the divertible flow allocated to the Upper Wyoming Section Diversions.

d. The Beckwith Quinn West Side Canal, which diverts water from the main stem of Bear River in Utah to irrigate lands in both Utah and Wyoming, shall be supplied from the divertible flow allocated to the Lower Utah Section Diversions.

e. If for any reason the aggregate of all diversions in a river section of the upper Division does not equal the allocation of water thereto, the unused portion of such allocation shall be

available for use in the other river sections in the Upper Division in the following order: (1) in the other river section of the same State in which the unused allocation occurs; and (2) in the river sections of the other State. No permanent right of use shall be established by the distribution of water pursuant to this paragraph e.

f. Water allocated to the several sections shall be distributed in each section in accordance with state law.

2. Central Division

a. When either the divertible flow as hereinafter defined for the Central Division is less than 870 second-feet, or the flow of the Bear River at Border Gaging Station is less than 350 second-feet, whichever shall first occur, a water emergency shall be deemed to exist in the Central Division and the total of all diversions in Wyoming from Grade Creek, Pine Creek, Bruner Creek and Pine Creek Springs, Spring Creek, Sublette Creek, Smiths Fork, and all the tributaries of Smiths Fork above the mouth of Hobble Creek including Hobble Creek, and from the main stem of the Bear River between Pixley Dam and the point where the river crosses the Wyoming-Idaho state line near Border shall be limited for the benefit of the State of Idaho, to not exceeding forty-three (43) percent of the divertible flow. The remaining fifty-seven (57) percent of the divertible flow shall be available for use in Idaho in the Central Division, but if any portion of such allocation is not used therein, it shall be available for use in Idaho in the Lower Division.

The divertible flow for the Central Division shall be the total of the following three items:

(1) Diversions in second-feet in Wyoming consisting of the sum of all diversions from Grade Creek, Pine Creek, Bruner Creek and Pine Creek Springs, Spring Creek, Sublette Creek, and Smiths Fork and all the tributaries of Smiths Fork above the mouth of Hobble Creek including Hobble Creek, and the main stem of the Bear River between Pixley Dam and the point where the river crosses the Wyoming-Idaho state line near Border, Wyoming.

(2) Diversions in second-feet in Idaho from the Bear River main stem from the point where the river crosses the Wyoming-Idaho state line near Border to Stewart Dam including West Fork Canal, which diverts at Stewart Dam.

(3) Flow in second-feet of the Rainbow Inlet Canal and of the Bear River passing downstream from Stewart Dam.

b. The Cook Canal, which diverts water from the main stem of the Bear River in Wyoming to irrigate lands in both Wyoming and Idaho, shall be considered a Wyoming diversion and shall be supplied from the divertible flow allocated to Wyoming.

c. Water allocated to each state shall be distributed in accordance with state law.

3. Lower Division

a. When the flow of water across the Idaho-Utah boundary line is insufficient to satisfy water rights in Utah, covering water applied to beneficial use prior to January 1, 1976, any water user in Utah may file a petition with the Commission alleging that by reason of diversions in Idaho he is being deprived of water to which he is justly entitled, and that by reason thereof, a water emergency exists, and requesting distribution of water under the direction of the Commission. If the Commission finds a water emergency exists, it shall put into effect water delivery schedules based on priority of rights and prepared by the Commission without regard to the boundary line for all or any part of the Division, and during such emergency,

water shall be delivered in accordance with such schedules by the state official charged with the administration of public waters.

B. The Commission shall have authority upon its own motion (1) to declare a water emergency in any or all river divisions based upon its determination that there are diversions which violate this Compact and which encroach upon water rights in a lower State, (2) to make appropriate orders to prevent such encroachments, and (3) to enforce such orders by action before State administrative officials or by court proceedings.

C. When the flow of water in an interstate tributary across a state boundary line is insufficient to satisfy water rights on such tributary in a lower State, any water user may file a petition with the Commission alleging that by reason of diversions in an upstream State he is being deprived of water to which he is justly entitled and that by reason thereof a water emergency exists, and requesting distribution of water under the direction of the Commission. If the Commission finds that a water emergency exists and that interstate control of water of such tributary is necessary, it shall put into effect water delivery schedules based on priority of rights and prepared without regard to the State boundary line. The State officials in charge of water distribution on interstate tributaries may appoint and fix the compensation and expenses of a joint water commissioner for each tributary. The proportion of the compensation and expenses to be paid by each State shall be determined by the ratio between the number of acres therein which are irrigated by diversions from such tributary, and the total number of acres irrigated from such tributary.

D. In preparing interstate water delivery schedules, the Commission, upon notice and after public hearings, shall make findings of fact as to the nature, priority and extent of water rights, rates of flow, duty of water, irrigated acreages, types of crops, time of use, and related matters; provided that such schedules shall recognize and incorporate therein priority of water rights as adjudicated in each of the signatory States. Such findings of fact shall, in any court or before any tribunal, constitute prima facie evidence of the facts found.

E. Water emergencies provided for herein shall terminate on September 30 of each year unless terminated sooner or extended by the Commission.

ARTICLE V

A. Water rights in the Lower Division acquired under the laws of Idaho and Utah covering water applied to beneficial use prior to January 1, 1976, are hereby recognized and shall be administered in accordance with state law based on priority of rights as provided in Article IV, paragraph A.3. Rights to water first applied to beneficial use on or after January 1, 1976, shall be satisfied from the respective allocations made to Idaho and Utah in this paragraph and the water allocated to each State shall be administered in accordance with State law. Subject to the foregoing provisions, the remaining water in the Lower Division, including ground water tributary to the Bear River, is hereby apportioned for use in Idaho and Utah as follows:

(1) Idaho shall have the first right to the use of such remaining water resulting in an annual depletion of not more than 125,000 acre-feet; (2) Utah shall have the second right to the use of such remaining water resulting in an annual depletion of not more than 275,000 acre-feet;

(3) Idaho and Utah shall each have an additional right to deplete annually on an equal basis, 75,000 acre-feet of the remaining water after the rights provided by subparagraphs (1), and (2) above have been satisfied;

(4) Any remaining water in the Lower Division after the allocations provided for in subparagraphs (1), (2), and (3) above have been satisfied shall be divided; thirty (30) percent to Idaho and seventy (70) percent to Utah.

B. Water allocated under the above subparagraphs shall be charged against the State in which it is used regardless of the location of the point of diversion.

C. Water depletions permitted under provisions of subparagraphs (1), (2), and (3), and (4) above, shall be calculated and administered by a Commission-approved procedure.

ARTICLE VI

A. Existing storage rights in reservoirs constructed above Stewart Dam prior to February 4, 1955 are as follows:

Idaho .... 324 acre-feet
Utah................................... 11,850 acre-feet
Wyoming .... 2,150 acre-feet

Additional rights are hereby granted to store in any water year above Stewart Dam, 35,500 acre-feet of Bear River water and no more under this paragraph for use in Utah and Wyoming; and to store in any water year in Idaho or Wyoming on Thomas Fork 1,000 acre-feet of water for use in Idaho. Such additional storage rights shall be subordinate to, and shall not be exercised when the effect thereof will be to impair or interfere with (1) existing direct flow rights for consumptive use in any river division and (2) existing storage rights above Stewart Dam, but shall not be subordinate to any right to store water in Bear Lake or elsewhere below Stewart Dam. One-half of the 35,500 acre-feet of additional storage right above Stewart Dam so granted to Utah and Wyoming is hereby allocated to Utah, and the remaining one-half thereof is allocated to Wyoming.

B. In addition to the rights defined in Paragraph A. of this Article, further storage entitlements above Stewart Dam are hereby granted. Wyoming and Utah are granted an additional right to store in any year 70,000 acre-feet of Bear River, water for use in Utah and Wyoming to be divided equally; and Idaho is granted an additional right to store 4,500 acre-feet of Bear River water in Wyoming or Idaho for use in Idaho. Water rights granted under this paragraph and water appropriated, including ground water tributary to Bear River, which is applied to beneficial use on or after January 1, 1976, shall not result in an annual increase in depletion of the flow of the Bear River and its tributaries above Stewart Dam of more than 28,000 acre-feet in excess of the depletion as of January 1, 1976. Thirteen thousand (13,000) acre-feet of the additional depletion above Stewart Dam is allocated to each of Utah and Wyoming, and two thousand (2,000) acre-feet is allocated to Idaho.

The additional storage rights provided for in this paragraph shall be subordinate to, and shall not be exercised when the effect thereof will be to impair or interfere with (1) existing direct flow rights for consumptive use in any river division and (2) existing storage rights above Stewart Dam, but shall not be subordinate to any right to store water in Bear Lake or elsewhere below Stewart Dam; provided, however, there shall be no diversion of water to storage above Stewart Dam under this paragraph B. when the water surface elevation of Bear Lake is below 5,911.00 feet, Utah Power & Light Company datum (the equivalent of elevation 5,913.75 feet based on the sea level datum of 1929 through the Pacific Northwest Supplementary Adjustment of 1947). Water depletions permitted under this paragraph B. shall be calculated and administered by a

Commission-approved procedure.

C. In addition to the rights defined in Article VI, paragraphs A. and B., Idaho, Utah and Wyoming are granted the right to store and use water above Stewart Dam that otherwise would be by-passed or released from Bear Lake at times when all other direct flow and storage rights are satisfied. The availability of such water and the operation of reservoir space to store water above Bear Lake under this paragraph shall be determined by a Commission-approved proce-dure. The storage provided for in this paragraph shall be subordinate to all other storage and direct flow rights in the Bear River. Storage rights under this paragraph shall be exercised with equal priority on the following basis: six (6) percent thereof to Idaho; forty-seven (47) percent thereof to Utah; and forty-seven (47) percent thereof to Wyoming.

D. The waters of Bear Lake below elevation 5,912.91 feet, Utah Power & Light Company Bear Lake datum (the equivalent of elevation 5915.66 feet based on the sea level datum of 1929 through the Pacific Northwest Supplementary Adjustment of 1947) shall constitute a reserve for irrigation. The water of such reserve shall not be released solely for the generation of power, except in emergency, but after release for irrigation, it may be used in generating power if not inconsistent with its use for irrigation. Any water in Bear Lake in excess of that constituting the irrigation reserve may be used for the generation of power or for other beneficial uses. As new reservoir capacity above the Stewart Dam is constructed to provide additional storage pursuant to paragraph A. of this article, the Commission shall make a finding in writing as to the quantity of additional storage and shall thereupon make an order increasing the irrigation reserve in ac-cordance with the following table:

Additional Storage acre-feet	Lake surface elevation Utah Power & Light Company Bear Lake datum
5,000	5,913.24
10,000	5,913.56
15,000	5,913.87
20,000	5,914.15
25,000	5,914.41
30,000	5,914.61
35,500	5,914.69
36,500	5,914.70

E. Subject to existing rights, each State shall have the use of water, including ground water, for or-dinary domestic, and stock watering purposes, as determined by State law and shall have the right to impound water for such purposes in reservoirs having storage capacities not in excess, in any case, of 20 acre-feet, without deduction from the allocation made by paragraphs A., B. and C. of this Article.

F. The storage rights in Bear Lake are hereby recognized and confirmed subject only to the re-strictions hereinbefore recited.

ARTICLE VII

It is the policy of the signatory States to encourage additional projects for the development of the water

resources of the Bear River to obtain the maximum beneficial use of water with a minimum of waste, and in furtherance of such policy, authority is granted within the limitations provided by this Compact, to investigate, plan, construct, and operate such projects without regard to state boundaries, provided that water rights for each such project shall, except as provided in Article VI, paragraphs A. and B. thereof, be subject to rights theretofore initiated and in good standing.

ARTICLE VIII

A. No state shall deny the right of the United States of America, and subject to the conditions hereinafter contained, no state shall deny the right of another signatory state, any person or entity of another signatory state, to acquire rights to the use of water or to construct or to participate in the construction and use of diversion works and storage reservoirs with appurtenant works, canals, and conduits in one state for use of water in another state, either directly or by exchange. Water rights acquired for out-of-state use shall be appropriated in the state where the point of diversion is located in the manner provided by law for appropriation of water for use within such state.

B. Any signatory state, any person or any entity of any signatory state, shall have the right to acquire in any other signatory state such property rights as are necessary to the use of water in conformity with this Compact by donation, purchase, or, as hereinafter provided through the exercise of the power of eminent domain in accordance with the law of the state in which such property is located. Any signatory state, upon the written request of the governor of any other signatory state for the benefit of whose water users property is to be acquired in the state to which such written request is made, shall proceed expeditiously to acquire the desired property either by purchase at a price acceptable to the requesting governor, or if such purchase cannot be made, then through the exercise of its power of eminent domain and shall convey such property to the requesting state or to the person, or entity designated by its governor provided, that all costs of acquisition and expenses of every kind and nature whatsoever incurred in obtaining such property shall be paid by the requesting state or the person or entity designated by its governor.

C. Should any facility be constructed in a signatory state by and for the benefit of another signatory state or persons or entities therein, as above provided, the construction, repair, replacement, maintenance and operation of such facility shall be subject to the laws of the state in which the facility is located.

D. In the event lands or other taxable facilities are acquired by a signatory state in another signatory state for the use and benefit of the former, the users of the water made available by such facilities, as a condition precedent to the use thereof, shall pay to the political subdivisions of the state in which such facilities are located, each and every year during which such rights are enjoyed for such purposes, a sum of money equivalent to the average of the amount of taxes annually levied and assessed against the land and improvements thereon during the ten years preceding the acquisition of such land. Said payments shall be in full reimbursement for the loss of taxes in such political subdivision of the state.

E. Rights to the use of water acquired under this Article shall in all respects be subject to this Compact.

ARTICLE IX

Stored water, or water from another watershed may be turned into the channel of the Bear River in one

state and a like quantity, with allowance for loss by evaporation, transpiration, and seepage, may be taken out of the Bear River in another state either above or below the point where the water is turned into the channel, but in making such exchange the replacement water shall not be inferior in quality for the purpose used or diminished in quantity. Exchanges shall not be permitted if the effect thereof is to impair vested rights or to cause damage for which no compensation is paid. Water from another watershed or source, which enters the Bear River by actions within a state, may be claimed exclusively by that state and use thereof by that state shall not be subject to the depletion limitations of Articles IV, V and VI. Proof of any claimed increase in flow shall be the burden of the State making such claim, and it shall be approved only by the unanimous vote of the Commission.

ARTICLE X

A. The following rights to the use of Bear River water carried in interstate canals are recognized and confirmed.

| Name of Canal | Date of Priority | Primary right second –feet | Lands Irrigated | |
			Acres	State
Hilliard East Fork	1914	28.00	2,644	Wyoming
Chapman	8-13-86	16.46	1,155	Wyoming
	8-13-86	98.46	6,892	Utah
	4-12-12	.57	40	Wyoming
	5- 3-12	4.07	285	Utah
	5-21-12	10.17	712	Utah
	2- 6-13	.79	55	Wyoming
	8-28-05	[1]134.00		
Francis Lee	1879	2.20	154	Wyoming
	1879	7.41	519	Utah

[1]Under the right as herein confirmed not to exceed 134 second-feet may be carried across the Wyoming-Utah state line in the Chapman Canal at any time for filling the Neponset Reservoir, for irrigation of land in Utah and for other purposes. The storage right in Neponset Reservoir is for 6,900 acre-feet, which is a component part of the irrigation right for the Utah lands listed above.

All other rights to the use of water carried in interstate canals and ditches, as adjudicated in the State in which the point of Diversion is located, are recognized and confirmed.

B. All interstate rights shall be administered by the State in which the point of diversion is located and during times of water emergency, such rights shall be filled from the allocations specified in Article IV hereof for the section in which the point of diversion is located, with the exception

that the diversion of water into the Hilliard East Fork Canal, Lannon Canal, Lone Mountain Ditch, and Hilliard West Side Canal shall be under the administration of Wyoming. During times of water emergency, these canals and the Lone Mountain Ditch shall be supplied from the allocation specified in Article IV for the Upper Wyoming Section Diversions.

ARTICLE XI

Applications for appropriation, for change of point of diversion, place and nature of use, and for exchange of Bear River water shall be considered and acted upon in accordance with the law of the state in which the point of diversion is located, but no such application shall be approved if the effect thereof will be to deprive any water user in another state of water to which he is entitled, nor shall any such application be approved if the effect thereof will be an increase in the depletion of the flow of the Bear River and its tributaries beyond the limits authorized in each State in Articles IV, V and VI of this Compact. The official of each state in charge of water administration shall, at intervals and in the format established by the Commission, report on the status of use of the respective allocations.

ARTICLE XII

Nothing in this compact shall be construed to prevent the United States, a signatory state or political subdivision thereof, person, corporation, or association, from instituting or maintaining any action or proceeding, legal or equitable, for the protection of any right under state or federal law or under this Compact.

ARTICLE XIII

Nothing contained in this Compact shall be deemed:
1. To affect the obligations of the United States of America to the Indian tribes;
2. To impair, extend or otherwise affect any right or power of the United States, its agencies or instrumentalities involved herein; nor the capacity of the United States to hold or acquire additional rights to the use of the water of the Bear River;
3. To subject any property or rights of the United States to the laws of the States which were not subject thereto prior to the date of this Compact;
4. To subject any property of the United States to taxation by the states or any subdivision thereof, nor to obligate the United States to pay any state or subdivision thereof for loss of taxes.

ARTICLE XIV

At intervals not exceeding twenty years, the Commission shall review the provisions hereof, and after notice and public hearing, may propose amendments to any such provision, provided, however, that the provisions contained herein shall remain in full force and effect until such proposed amendments have been ratified by the legislatures of the signatory States and consented to by Congress.

ARTICLE XV

This Compact may be terminated at any time by the unanimous agreement of the signatory states. In the event of such termination, all rights established under it shall continue unimpaired.

ARTICLE XVI

Should a court of competent jurisdiction hold any part of this Compact to be contrary to the constitution of any signatory State or to the Constitution of the United States, all other severable provisions of this Compact shall continue in full force and effect.

ARTICLE XVII

This Compact shall be in effect when it shall have been ratified by the legislature of each signatory state and consented to by the Congress of the United States of America. Notice of ratification by the legislature of the signatory states shall be given by the governor of each signatory state to the governor of each of the other signatory states and to the President of the United States of America, and the President is hereby requested to give notice to the governor of each of the signatory states of approval by the Congress of the United States of America.

IN WITNESS WHEREOF, the Commissioners and their advisers have executed this Compact in five originals, one of which shall be deposited with the General Services Administration of the United States of America, one of which shall be forwarded to the governor of each of the signatory states, and one of which shall be made a part of the permanent records of the Bear River Commission.

Done at Salt Lake City, Utah, this 22nd day of December 1978.

For the State of Idaho:
CLIFFORD J. SKINNER
J. DANIEL ROBERTS
DON W. GILBERT

For the State of Utah:
S. PAUL HOLMGREN
SIMEON WESTON
DANIEL F. LAWRENCE

For the State of Wyoming:
GEORGE L. CHRISTOPULOS
J. W. MYERS
JOHN A. TEICHERT

Approved:
WALLACE N. JIBSON
Representative of the United States of America
Attest:
DANIEL F. LAWRENCE

Secretary of the Bear River Compact Commission

Congressional Consent to Negotiations. --- By the Act of July 24, 1946, (60 Stat. 658), the Congress gave its consent to the negotiation by the States of Idaho, Utah, and Wyoming of a compact "providing for an equitable division and apportionment among the said States of the waters of the Bear River and all of its tributaries in the three States ***." This consent was given "upon condition that one suitable person from the Department of the Interior, who shall be appointed by the President of the United States, shall participate in said negotiations as the representative of the United States and shall make report to Congress of the proceedings and of any compact entered into." The Act cited also provided that no such compact should be effective until it had been ratified by the legislature of each of the states and "approved" by the Congress.

Congressional Consent to the Compact. --- The Compact set out above is an amended Compact. Consent to the original Compact was given in the Act of March 17, 1958 (72 Stat. 38). The remaining sections of this act read as follows:

SEC. 2. All officers, agencies, departments, and persons of and in the United States Government shall cooperate with the Bear River Commission, established pursuant to the compact consented to hereby, in any manner authorized by law other than this Act, it being the purpose of Congress: that the United States Government shall assist in the furtherance of the objectives of a Bear River Compact and in the work of the commission created thereby.

SEC. 3. Any modification of the allocation of storage rights contained in Article V shall become effective only when consented to by the Congress.

SEC. 4. The right to alter, amend, or repeal this Act is expressly reserved. Consent to the Amended Compact was given in the Act of February 8, 1980, (94 Stat. 4) from which the text of the Compact set out above is taken.

Legislative History of the Compact. --- For legislative history of the original Compact, see Sl086, and HR 4647, HR 5379, HR 6381, 15th Congress; House Report 1375 (Committee on Interior and Insular Affairs) and Senate Report 843 (Committee on Interior and Insular Affairs), 85th Congress; Congressional Record, vols. 103 and 104.

For legislative history of the Amended Compact, see S1489, and HR 4320, 96th Congress; House Report 96-524 (Committee on Interior and Insular Affairs) and Senate Report 96-526 (Committee on the Judiciary), 96th Congress; Congressional Record vols. 125 and 126.

Appendix E
Environmental Water Samples

Appendix E. Summary statistics for environmental water samples, Bear River Basin, Wyoming.—

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; CaCO₃, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary alluvial aquifers	Dissolved oxygen	0.10	0.10	0.75	4.0	5.0	6
	pH (standard units)	7.1	7.4	7.5	7.7	8.3	39
	Specific conductance (µS/cm)	365	592	724	1,060	2,610	39
	Hardness (as CaCO₃)	152	270	320	390	980	29
	Calcium	41.0	64.0	76.0	88.0	150	29
	Magnesium	12.0	23.0	32.0	46.0	150	29
	Sodium	3.5	20.0	39.0	74.0	240	29
	Potassium	0.70	1.4	1.7	3.2	6.6	20
	Sodium adsorption ratio (unitless)	0.10	0.40	0.75	1.5	2.8	18
	Alkalinity (as CaCO₃)	157	228	297	324	502	29
	Chloride	3.0	13.0	32.2	84.0	290	29
	Fluoride	0.10	0.12	0.30	0.35	1.0	20
	Silica	7.9	12.0	16.0	18.0	26.0	21
	Sulfate	7.2	29.0	52.0	110	700	29
	Total dissolved solids	212	354	458	540	1,770	29
	Ammonia (as N)	--	0.01	0.02	0.02	0.04	13
	Nitrate plus nitrite (as N)	--	0.15	0.89	2.3	59.2	18
	Nitrate (as N)	--	0.06	0.30	1.4	17.0	26
	Nitrite (as N)	--	0.001	0.002	0.005	0.03	16
	Orthophosphate (as P)	--	0.01	0.02	0.02	0.03	13
	Phosphorus, unfiltered	0.03	--	--	--	0.04	2
	Arsenic	--	--	--	--	2.0	3
	Barium	25.0	--	350	--	460	3
	Boron	--	50.0	70.0	90.0	250	9
	Cadmium	--	--	--	--	<1.0	3
	Copper	--	--	--	--	<10.0	3
	Iron	--	1.5	9.0	30.0	7,400	14
	Iron, unfiltered	--	8.0	28.0	54.8	6,400	14
	Lead	--	--	--	--	4.0	3
	Manganese	--	0.25	0.91	3.3	63.0	11
	Manganese, unfiltered	160	--	--	--	--	1
	Mercury	--	--	--	--	2.1	3
	Nickel	--	--	--	--	<30.0	3
	Selenium	--	--	--	--	<5.0	5
	Silver	--	--	--	--	<1.0	3
	Zinc	5.0	--	20.0	--	40.0	3
Quaternary terrace-deposit aquifers	pH (standard units)	7.4	7.5	7.7	7.7	8.6	10
	Specific conductance (µS/cm)	516	601	827	1,010	1,540	10
	Hardness (as CaCO₃)	262	300	326	342	410	10
	Calcium	49.0	60.0	67.0	81.0	84.0	10

Appendix E. Summary statistics for environmental water samples, Bear River Basin, Wyoming. —Continued

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; μS/cm, microsiemens per centimeter at 25 degrees Celsius; CaCO₃, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Quaternary terrace-deposit aquifers—Continued	Magnesium	22.0	26.0	39.5	43.0	66.0	10
	Sodium	8.1	9.6	52.0	77.0	200	10
	Potassium	0.80	--	1.8	--	2.6	3
	Sodium adsorption ratio (unitless)	0.20	0.21	0.70	1.7	4.5	7
	Alkalinity (as CaCO₃)	202	209	262	285	316	10
	Chloride	5.7	10.0	51.0	90.0	130	10
	Fluoride	0.20	--	0.30	--	0.90	3
	Silica	11.0	14.0	17.5	24.0	30.0	4
	Sulfate	52.0	52.0	75.0	100	400	10
	Total dissolved solids	297	386	476	539	1,030	10
	Ammonia (as N)	0.08	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.08	--	--	--	--	1
	Nitrate (as N)	--	0.63	4.9	10.4	41.0	8
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.03	--	--	--	--	1
	Boron	50.0	--	--	--	--	1
	Iron	<3.0	--	--	--	120	2
	Iron, unfiltered	10.0	10.0	10.0	25.0	40.0	4
	Manganese	5.0	--	--	--	51.0	2
Quaternary landslide deposits	pH (standard units)	8.0	--	--	--	--	1
	Specific conductance (μS/cm)	328	--	--	--	--	1
	Hardness (as CaCO₃)	162	--	--	--	--	1
	Calcium	45.0	--	--	--	--	1
	Magnesium	12.0	--	--	--	--	1
	Sodium	1.4	--	--	--	--	1
	Potassium	0.50	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.05	--	--	--	--	1
	Alkalinity (as CaCO₃)	108	--	--	--	--	1
	Chloride	0.50	--	--	--	--	1
	Fluoride	0.10	--	--	--	--	1
	Silica	5.4	--	--	--	--	1
	Sulfate	60.0	--	--	--	--	1
	Total dissolved solids	187	--	--	--	--	1
Fowkes aquifer	pH (standard units)	7.3	7.4	7.8	7.9	8.2	7
	Specific conductance (μS/cm)	385	525	696	980	2,820	7
	Hardness (as CaCO₃)	186	240	263	288	400	6
	Calcium	48.4	53.0	61.0	73.0	88.0	6
	Magnesium	14.7	24.0	25.5	30.2	43.2	6
	Sodium	17.0	18.7	68.0	135	490	6
	Potassium	1.6	3.5	5.1	6.6	20.7	5

Appendix E. Summary statistics for environmental water samples, Bear River Basin, Wyoming.—Continued

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; μS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Fowkes aquifer—Continued	Sodium adsorption ratio (unitless)	0.44	--	--	--	1.6	2
	Alkalinity (as $CaCO_3$)	153	178	250	312	334	6
	Chloride	21.9	23.0	98.0	166	710	6
	Fluoride	0.06	0.27	0.40	0.40	0.45	5
	Silica	10.0	36.3	41.0	41.5	59.0	5
	Sulfate	13.0	46.5	51.5	52.0	190	6
	Total dissolved solids	248	350	537	640	1,570	6
	Nitrate (as N)	0.14	0.24	0.32	0.90	1.7	5
	Nitrite (as N)	<0.02	--	--	--	0.05	2
	Arsenic	--	--	--	--	4.0	3
	Barium	13.0	--	189	--	250	3
	Boron	20.0	--	60.0	--	155	3
	Cadmium	--	--	--	--	<1.0	3
	Chromium	<1.0	--	--	--	3.0	2
	Copper	--	--	--	--	<10.0	3
	Iron	--	11.0	41.3	96.0	125	4
	Iron, unfiltered	--	46.4	129	217	235	4
	Lead	--	--	--	--	<1.0	3
	Manganese	--	9.5	10.0	12.0	14.0	4
	Mercury	--	--	--	--	<0.20	3
	Nickel	--	--	--	--	<30.0	3
	Selenium	--	--	--	--	<1.0	3
	Silver	--	--	--	--	<1.0	3
	Zinc	15.0	--	20.0	--	35.0	3
	Gross alpha radioactivity (picocuries per liter)	5.3	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	3.9	--	--	--	--	1
	Radium-226 (picocuries per liter)	<0.20	--	--	--	--	1
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Uranium	11.2	--	--	--	--	1
Angelo Member of the Green River Formation	pH (standard units)	7.4	--	--	--	--	1
	Specific conductance (μS/cm)	400	--	--	--	--	1
	Hardness (as $CaCO_3$)	210	--	--	--	--	1
	Calcium	46.0	--	--	--	--	1
	Magnesium	23.0	--	--	--	--	1
	Sodium	11.0	--	--	--	--	1
	Potassium	2.4	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.30	--	--	--	--	1
	Alkalinity (as $CaCO_3$)	210	--	--	--	--	1

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; CaCO₃, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Angelo Member of the Green River Formation—Continued	Chloride	5.0	--	--	--	--	1
	Fluoride	0.40	--	--	--	--	1
	Silica	14.0	--	--	--	--	1
	Sulfate	15.0	--	--	--	--	1
	Total dissolved solids	244	--	--	--	--	1
	Ammonia plus organic nitrogen (as N)	0.02	--	--	--	--	1
	Ammonia plus organic nitrogen, unfiltered (as N)	0.04	--	--	--	--	1
	Ammonia (as N)	<0.01	--	--	--	--	1
	Ammonia, unfiltered (as N)	<0.01	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.82	--	--	--	--	1
	Organic nitrogen	0.02	--	--	--	--	1
	Organic nitrogen, unfiltered	0.04	--	--	--	--	1
	Total nitrogen	0.84	--	--	--	--	1
	Total nitrogen, unfiltered	0.86	--	--	--	--	1
	Orthophosphate (as P)	0.02	--	--	--	--	1
	Phosphorus	0.01	--	--	--	--	1
	Phosphorus, unfiltered	0.01	--	--	--	--	1
	Boron	50.0	--	--	--	--	1
	Iron	20.0	--	--	--	--	1
	Manganese	<10.0	--	--	--	--	1
Fossil Butte Member of the Green River Formation	pH (standard units)	7.4	7.4	7.5	7.7	7.7	7
	Specific conductance (µS/cm)	623	976	1,040	1,130	1,210	7
	Hardness (as CaCO₃)	278	431	499	572	626	6
	Calcium	57.0	100	105	130	140	6
	Magnesium	33.0	44.0	56.0	63.0	67.0	6
	Sodium	9.7	18.0	32.5	45.0	53.0	6
	Potassium	0.40	1.3	1.9	2.4	2.8	6
	Sodium adsorption ratio (unitless)	0.25	0.31	0.65	0.84	1.1	6
	Alkalinity (as CaCO₃)	199	233	279	304	340	6
	Chloride	6.8	11.0	14.5	20.0	24.0	6
	Fluoride	0.20	0.30	0.30	0.30	0.50	6
	Silica	11.0	12.0	16.0	21.0	28.0	6
	Sulfate	87.0	260	280	400	400	6
	Total dissolved solids	333	704	751	826	908	6
	Iron	--	--	--	--	<3.0	5
	Manganese	--	--	--	--	2.0	5
Wasatch aquifer	pH (standard units)	7.1	7.5	7.7	8.0	8.6	22
	Specific conductance (µS/cm)	360	568	765	994	8,500	23
	Hardness (as CaCO₃)	10.0	240	322	360	900	21

Appendix E. Summary statistics for environmental water samples, Bear River Basin, Wyoming.—Continued

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; CaCO₃, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Wasatch aquifer— Continued	Calcium	3.1	49.0	58.0	80.0	200	21
	Magnesium	0.60	25.0	38.0	51.0	97.0	21
	Sodium	4.7	22.0	28.0	79.0	2,000	21
	Potassium	1.2	2.6	4.3	5.4	14.0	19
	Sodium adsorption ratio (unitless)	0.11	0.56	0.75	1.9	63.0	12
	Alkalinity (as CaCO₃)	180	217	273	301	384	21
	Chloride	8.7	18.0	31.0	59.0	2,700	21
	Fluoride	0.20	0.30	0.40	0.67	1.9	18
	Silica	3.7	6.5	8.8	13.0	45.4	18
	Sulfate	4.1	22.0	44.0	100	790	21
	Total dissolved solids	176	313	411	543	5,400	20
	Ammonia (as N)	0.07	0.14	0.70	1.4	1.6	4
	Ammonia, unfiltered (as N)	1.8	--	--	--	--	1
	Nitrate plus nitrite (as N)	--	0.04	0.09	0.34	1.1	6
	Nitrate (as N)	--	0.16	0.29	0.59	2.7	13
	Nitrite (as N)	--	--	--	--	0.19	5
	Orthophosphate (as P)	0.01	--	--	--	--	1
	Aluminum	--	--	--	--	<4,500	3
	Antimony	<3.0	--	--	--	--	1
	Arsenic	--	--	--	--	16.0	7
	Barium	--	58.0	103	200	420	7
	Beryllium	--	--	--	--	<6.0	2
	Boron	--	49.0	105	140	460	14
	Cadmium	--	--	--	--	<10.0	6
	Chromium	--	--	--	--	<50.0	5
	Cobalt	<10.0	--	--	--	--	1
	Copper	--	--	--	--	20.0	5
	Cyanide	--	--	--	--	<0.01	2
	Iron	--	6.2	130	690	1,600	13
	Iron, unfiltered	--	32.9	150	420	7,800	10
	Lead	--	--	--	--	<50.0	7
	Lithium	60.0	--	--	--	--	1
	Manganese	--	0.82	3.3	20.0	200	9
	Manganese, unfiltered	<10.0	--	--	--	220	2
	Mercury	--	--	--	--	<1.0	7
	Nickel	--	--	--	--	60.0	5
	Selenium	--	--	--	--	<10.0	7
	Silver	--	--	--	--	<20.0	6
	Thallium	<1.0	--	--	--	--	1

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; CaCO$_3$, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Wasatch aquifer— Continued	Vanadium	<10.0	--	--	--	--	1
	Zinc	20.0	22.0	30.0	180	1,100	5
	Gross alpha radioactivity (picocuries per liter)	1.8	--	--	--	9.0	2
	Gross beta radioactivity (picocuries per liter)	<2.0	--	--	--	19.0	2
	Radium-226 (picocuries per liter)	0.90	--	--	--	2.9	2
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Radon-222, unfiltered (picocuries per liter)	380	--	--	--	--	1
	Uranium	--	--	--	--	<300	3
Evanston aquifer	pH (standard units)	7.4	--	--	--	8.3	2
	Specific conductance (µS/cm)	985	--	--	--	7,590	2
	Hardness (as CaCO$_3$)	194	--	--	--	413	2
	Calcium	30.0	--	--	--	88.0	2
	Magnesium	29.0	--	--	--	47.0	2
	Sodium	48.0	--	--	--	1,800	2
	Potassium	3.1	--	--	--	23.0	2
	Sodium adsorption ratio (unitless)	1.0	--	--	--	56.2	2
	Alkalinity (as CaCO$_3$)	277	--	--	--	525	2
	Chloride	30.0	--	--	--	1,600	2
	Fluoride	0.50	--	--	--	2.2	2
	Silica	4.7	--	--	--	12.0	2
	Sulfate	230	--	--	--	1,100	2
	Total dissolved solids	662	--	--	--	4,880	2
	Ammonia (as N)	1.1	--	--	--	--	1
	Nitrate plus nitrite (as N)	<0.05	--	--	--	--	1
	Nitrate (as N)	<0.05	--	--	--	--	1
	Nitrite (as N)	<0.01	--	--	--	--	1
	Orthophosphate (as P)	0.02	--	--	--	--	1
	Iron	<3.0	--	--	--	510	2
	Manganese	<1.0	--	--	--	70.0	2
Frontier aquifer	pH (standard units)	8.1	--	--	--	--	1
	Specific conductance (µS/cm)	910	--	--	--	--	1
	Hardness (as CaCO$_3$)	384	--	--	--	--	1
	Calcium	50.0	--	--	--	--	1
	Magnesium	63.0	--	--	--	--	1
	Sodium	102	--	--	--	--	1
	Potassium	14.0	--	--	--	--	1
	Alkalinity (as CaCO$_3$)	334	--	--	--	--	1
	Chloride	23.0	--	--	--	--	1

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; μS/cm, microsiemens per centimeter at 25 degrees Celsius; CaCO₃, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Frontier aquifer—Continued	Fluoride	0.74	--	--	--	--	1
	Sulfate	256	--	--	--	--	1
	Total dissolved solids	608	--	--	--	--	1
	Nitrate (as N)	0.22	--	--	--	--	1
	Arsenic	<10.0	--	--	--	--	1
	Barium	<50.0	--	--	--	--	1
	Cadmium	<10.0	--	--	--	--	1
	Chromium	<50.0	--	--	--	--	1
	Lead	<50.0	--	--	--	--	1
	Mercury	<1.0	--	--	--	--	1
	Selenium	<10.0	--	--	--	--	1
	Silver	<20.0	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	23.0	--	--	--	--	1
	Gross beta radioactivity (picocuries per liter)	20.0	--	--	--	--	1
	Radium-226 (picocuries per liter)	0.60	--	--	--	--	1
	Uranium	20.0	--	--	--	--	1
Sage Junction Formation	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (μS/cm)	857	--	--	--	--	1
	Hardness (as CaCO₃)	386	--	--	--	--	1
	Calcium	100	--	--	--	--	1
	Magnesium	33.0	--	--	--	--	1
	Sodium	27.0	--	--	--	--	1
	Potassium	2.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.60	--	--	--	--	1
	Alkalinity (as CaCO₃)	285	--	--	--	--	1
	Chloride	65.0	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	7.7	--	--	--	--	1
	Sulfate	38.0	--	--	--	--	1
	Total dissolved solids	458	--	--	--	--	1
	Iron	<3.0	--	--	--	--	1
	Manganese	<1.0	--	--	--	--	1
Bear River aquifer	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (μS/cm)	615	--	--	--	--	1
	Hardness (as CaCO₃)	320	--	--	--	--	1
	Calcium	89.0	--	--	--	--	1
	Magnesium	25.0	--	--	--	--	1
	Sodium	11.0	--	--	--	--	1
	Potassium	1.1	--	--	--	--	1

Appendix E. Summary statistics for environmental water samples, Bear River Basin, Wyoming.—Continued

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; CaCO₃, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Bear River aquifer—Continued	Sodium adsorption ratio (unitless)	0.30	--	--	--	--	1
	Alkalinity (as CaCO₃)	199	--	--	--	--	1
	Chloride	3.9	--	--	--	--	1
	Fluoride	0.20	--	--	--	--	1
	Silica	13.0	--	--	--	--	1
	Sulfate	120	--	--	--	--	1
	Total dissolved solids	386	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.70	--	--	--	--	1
	Boron	60.0	--	--	--	--	1
	Iron, unfiltered	30.0	--	--	--	--	1
Thomas Fork aquifer	pH (standard units)	7.7	--	--	--	--	1
	Specific conductance (µS/cm)	560	--	--	--	670	2
	Hardness (as CaCO₃)	293	--	--	--	--	1
	Calcium	83.0	--	--	--	--	1
	Magnesium	21.0	--	--	--	--	1
	Sodium	6.5	--	--	--	--	1
	Potassium	0.90	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.17	--	--	--	--	1
	Alkalinity (as CaCO₃)	170	--	--	--	--	1
	Chloride	4.9	--	--	--	--	1
	Fluoride	0.19	--	--	--	--	1
	Silica	6.6	--	--	--	--	1
	Sulfate	129	--	--	--	--	1
	Total dissolved solids	390	--	--	--	--	1
	Nitrate plus nitrite (as N)	0.68	--	--	--	--	1
	Arsenic	<5.0	--	--	--	--	1
	Barium	<200	--	--	--	--	1
	Boron	<100	--	--	--	--	1
	Cadmium	<2.0	--	--	--	--	1
	Chromium	<10.0	--	--	--	--	1
	Copper	<20.0	--	--	--	--	1
	Iron	<50.0	--	--	--	--	1
	Lead	<5.0	--	--	--	--	1
	Manganese	<20.0	--	--	--	--	1
	Mercury	<1.0	--	--	--	--	1
	Selenium	<5.0	--	--	--	--	1
	Silver	<10.0	--	--	--	--	1
	Zinc	<20.0	--	--	--	--	1
	Gross alpha radioactivity (picocuries per liter)	<1.0	--	--	--	--	1

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; μS/cm, microsiemens per centimeter at 25 degrees Celsius; CaCO₃, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Thomas Fork aquifer—Continued	Gross beta radioactivity (picocuries per liter)	<1.0	--	--	--	--	1
	Radium-226 (picocuries per liter)	<0.20	--	--	--	--	1
	Radium-228 (picocuries per liter)	<1.0	--	--	--	--	1
	Uranium	<0.30	--	--	--	--	1
Gannett aquifer and confining unit	pH (standard units)	7.5	7.5	7.6	7.7	8.5	7
	Specific conductance (μS/cm)	430	479	526	780	1,460	8
	Hardness (as CaCO₃)	57.0	120	250	300	310	6
	Calcium	7.8	23.0	66.0	85.0	86.0	6
	Magnesium	9.1	14.0	19.0	23.0	25.0	6
	Sodium	6.8	7.1	10.4	65.0	280	6
	Potassium	0.70	1.1	1.1	1.7	4.3	6
	Sodium adsorption ratio (unitless)	0.40	--	2.6	--	16.1	3
	Alkalinity (as CaCO₃)	170	170	190	211	326	6
	Chloride	5.9	6.5	7.0	37.0	140	6
	Fluoride	0.20	0.21	0.30	0.80	2.3	6
	Silica	7.5	--	8.5	--	9.7	3
	Sulfate	7.0	25.0	129	134	180	6
	Total dissolved solids	243	291	376	388	854	6
	Nitrate plus nitrite (as N)	0.11	--	--	--	2.1	2
	Nitrate (as N)	0.02	--	--	--	--	1
	Arsenic	1.3	--	1.9	--	2.5	3
	Barium	--	--	--	--	<1,000	3
	Boron	30.0	--	--	--	50.0	2
	Cadmium	--	--	--	--	<10.0	3
	Chromium	--	--	--	--	<50.0	3
	Copper	--	--	--	--	<50.0	3
	Iron	--	--	--	--	270	5
	Iron, unfiltered	20.0	--	--	--	--	1
	Lead	--	--	--	--	<0.50	3
	Manganese	--	--	--	--	<50.0	4
	Mercury	--	--	--	--	<0.50	3
	Selenium	--	--	--	--	<0.50	3
	Silver	--	--	--	--	<50.0	3
	Zinc	--	--	--	--	<20.0	3
Preuss Sandstone or Redbeds	pH (standard units)	7.6	--	--	--	7.7	2
	Specific conductance (μS/cm)	1,260	--	--	--	1,350	2
	Hardness (as CaCO₃)	220	--	--	--	310	2
	Calcium	70.0	--	--	--	88.0	2
	Magnesium	12.0	--	--	--	21.0	2

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; µS/cm, microsie-mens per centimeter at 25 degrees Celsius; CaCO₃, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Preuss Sandstone or Redbeds—Continued	Sodium	150	--	--	--	170	2
	Potassium	1.2	--	--	--	2.3	2
	Sodium adsorption ratio (unitless)	3.7	--	--	--	4.9	2
	Alkalinity (as CaCO₃)	200	--	--	--	226	2
	Chloride	200	--	--	--	210	2
	Fluoride	0.10	--	--	--	0.20	2
	Silica	12.0	--	--	--	12.0	2
	Sulfate	67.0	--	--	--	99.0	2
	Total dissolved solids	664	--	--	--	715	2
	Nitrate plus nitrite (as N)	0.35	--	--	--	1.6	2
	Boron	40.0	--	--	--	40.0	2
	Iron, unfiltered	20.0	--	--	--	50.0	2
Twin Creek aquifer	pH (standard units)	7.4	--	--	--	7.6	2
	Specific conductance (µS/cm)	463	--	--	--	592	2
	Hardness (as CaCO₃)	208	--	--	--	293	2
	Calcium	65.0	--	--	--	76.0	2
	Magnesium	11.0	--	--	--	25.0	2
	Sodium	11.0	--	--	--	12.0	2
	Potassium	0.90	--	--	--	2.3	2
	Sodium adsorption ratio (unitless)	0.28	--	--	--	0.36	2
	Alkalinity (as CaCO₃)	150	--	--	--	223	2
	Chloride	7.7	--	--	--	11.0	2
	Fluoride	0.10	--	--	--	0.50	2
	Silica	14.0	--	--	--	15.0	2
	Sulfate	75.0	--	--	--	86.0	2
	Total dissolved solids	282	--	--	--	366	2
	Iron	36.0	--	--	--	800	2
	Manganese	<1.0	--	--	--	190	2
Nugget aquifer	pH (standard units)	6.2	7.4	7.7	8.1	8.1	6
	Specific conductance (µS/cm)	64.0	229	441	596	1,270	6
	Hardness (as CaCO₃)	24.6	100	202	288	357	5
	Calcium	7.7	31.0	61.0	71.0	77.0	5
	Magnesium	1.3	5.8	12.0	27.0	40.0	5
	Sodium	2.3	6.8	7.2	8.0	148	5
	Potassium	0.50	0.65	1.1	1.5	1.6	4
	Sodium adsorption ratio (unitless)	0.17	0.20	0.22	0.30	3.4	5
	Alkalinity (as CaCO₃)	21.0	98.0	153	210	300	5
	Chloride	1.9	3.8	9.1	11.0	50.0	5
	Fluoride	0.10	0.15	0.20	0.20	0.20	4
	Silica	9.1	11.1	13.5	15.5	17.0	4

Appendix E. Summary statistics for environmental water samples, Bear River Basin, Wyoming.—Continued

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; μS/cm, microsiemens per centimeter at 25 degrees Celsius; CaCO₃, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Nugget aquifer— Continued	Sulfate	4.1	9.1	13.0	110	328	5
	Total dissolved solids	54.0	143	210	384	824	5
	Nitrate (as N)	0.05	--	--	--	1.1	2
	Phosphorus, unfiltered	0.01	--	--	--	--	1
	Iron	<3.0	--	--	--	26.0	2
	Manganese	--	--	--	--	<1.0	2
Thaynes aquifer	pH (standard units)	7.4	7.4	7.7	7.9	7.9	4
	Specific conductance (μS/cm)	241	318	484	602	631	4
	Hardness (as CaCO₃)	123	166	256	307	310	4
	Calcium	35.0	46.0	63.0	72.0	75.0	4
	Magnesium	8.6	12.3	22.0	30.5	33.0	4
	Sodium	1.0	2.2	7.7	15.0	18.0	4
	Potassium	0.20	0.40	1.4	2.6	3.1	4
	Sodium adsorption ratio (unitless)	0.04	0.07	0.20	0.35	0.40	4
	Alkalinity (as CaCO₃)	120	161	205	224	240	4
	Chloride	0.30	0.95	4.7	8.0	8.3	4
	Fluoride	0.10	0.10	0.20	0.35	0.40	4
	Silica	4.7	7.1	9.5	11.8	14.0	4
	Sulfate	6.2	7.8	52.2	96.0	97.0	4
	Total dissolved solids	127	179	299	377	386	4
	Nitrate plus nitrite (as N)	0.02	--	--	--	--	1
	Boron	80.0	--	--	--	--	1
	Iron	<3.0	--	--	--	--	1
	Iron, unfiltered	700	--	--	--	--	1
	Manganese	<1.0	--	--	--	--	1
Woodside confining unit	pH (standard units)	7.7	--	--	--	7.8	2
	Specific conductance (μS/cm)	430	--	--	--	518	2
	Hardness (as CaCO₃)	250	--	--	--	--	1
	Calcium	54.0	--	--	--	--	1
	Magnesium	28.0	--	--	--	--	1
	Sodium	5.7	--	--	--	--	1
	Potassium	1.0	--	--	--	--	1
	Sodium adsorption ratio (unitless)	0.16	--	--	--	--	1
	Alkalinity (as CaCO₃)	222	--	--	--	--	1
	Chloride	3.6	--	--	--	--	1
	Fluoride	0.30	--	--	--	--	1
	Silica	11.0	--	--	--	--	1
	Sulfate	56.0	--	--	--	--	1
	Total dissolved solids	302	--	--	--	--	1
	Iron	<3.0	--	--	--	--	1

Summary statistics for environmental water samples, Bear River Basin, Wyoming.—Continued

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter; μS/cm, microsie-
mens per centimeter at 25 degrees Celsius; CaCO₃, calcium carbonate; N, nitrogen; P, phosphorus]

Hydrogeologic unit	Characterisitc or constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Woodside confining unit—Continued	Manganese	<1.0	--	--	--	--	1
Phosphoria aquifer	pH (standard units)	7.5	--	--	--	7.8	2
	Specific conductance (μS/cm)	1,650	--	--	--	4,830	2
	Hardness (as CaCO₃)	840	--	--	--	2,390	2
	Calcium	230	--	--	--	526	2
	Magnesium	65.0	--	--	--	262	2
	Sodium	70.0	--	--	--	424	2
	Potassium	7.9	--	--	--	51.0	2
	Sodium adsorption ratio (unitless)	1.1	--	--	--	3.8	2
	Alkalinity (as CaCO₃)	146	--	--	--	238	2
	Chloride	51.0	--	--	--	356	2
	Fluoride	0.80	--	--	--	2.6	2
	Silica	8.3	--	--	--	9.2	2
	Sulfate	650	--	--	--	2,620	2
	Total dissolved solids	1,230	--	--	--	4,560	2
	Nitrate plus nitrite (as N)	0.13	--	--	--	--	1
	Boron	<1.0	--	--	--	230	2
	Iron, unfiltered	20.0	--	--	--	--	1
Wells aquifer	pH (standard units)	7.4	--	--	--	8.1	2
	Specific conductance (μS/cm)	193	--	--	--	839	2
	Hardness (as CaCO₃)	100	--	--	--	330	2
	Calcium	29.0	--	--	--	75.0	2
	Magnesium	6.8	--	--	--	34.0	2
	Sodium	0.50	--	--	--	50.0	2
	Potassium	0.20	--	--	--	3.1	2
	Sodium adsorption ratio (unitless)	0.02	--	--	--	1.2	2
	Alkalinity (as CaCO₃)	225	--	--	--	--	1
	Chloride	3.1	--	--	--	48.0	2
	Fluoride	0.30	--	--	--	0.50	2
	Silica	5.3	--	--	--	12.0	2
	Sulfate	12.0	--	--	--	160	2
	Total dissolved solids	110	--	--	--	521	2
	Nitrate plus nitrite (as N)	0.83	--	--	--	--	1
	Boron	80.0	--	--	--	--	1
	Iron, unfiltered	40.0	--	--	--	--	1

Appendix F
Produced Water Samples

Appendix F. Summary statistics for produced-water samples, Bear River Basin, Wyoming.·

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

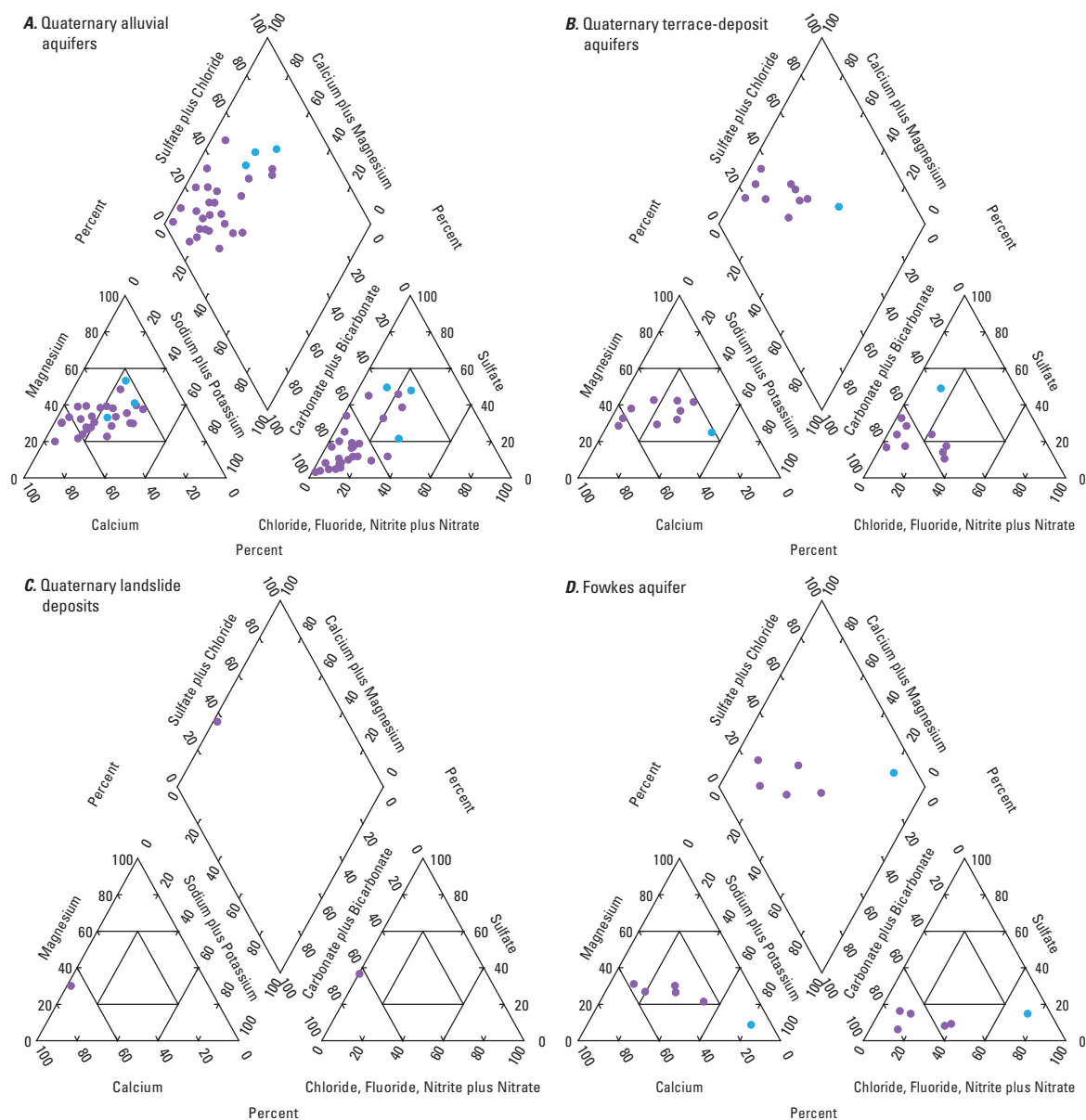| Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Evanston aquifer	pH (standard units)	7.1	--	--	--	--	1
	Calcium	342	--	--	--	--	1
	Magnesium	42.0	--	--	--	--	1
	Sodium	1,280	--	--	--	--	1
	Potassium	17.0	--	--	--	--	1
	Bicarbonate	579	--	--	--	--	1
	Chloride	2,300	--	--	--	--	1
	Sulfate	129	--	--	--	--	1
	Total dissolved solids	4,400	--	--	--	--	1
Frontier aquifer	pH (standard units)	8.2	--	--	--	--	1
	Calcium	305	--	--	--	--	1
	Magnesium	77.0	--	--	--	--	1
	Sodium	3,880	--	--	--	--	1
	Potassium	112	--	--	--	--	1
	Bicarbonate	1,170	--	--	--	--	1
	Chloride	4,900	--	--	--	--	1
	Sulfate	1,700	--	--	--	--	1
	Total dissolved solids	11,600	--	--	--	--	1
Aspen confining unit	pH (standard units)	8.1	--	--	--	8.4	2
	Calcium	1,060	--	--	--	1,100	2
	Magnesium	206	--	--	--	299	2
	Sodium	9,600	--	--	--	10,800	2
	Bicarbonate	1,800	--	--	--	1,820	2
	Chloride	16,500	--	--	--	18,000	2
	Sulfate	9.0	--	--	--	--	1
	Total dissolved solids	28,300	--	--	--	31,000	2
Bear River aquifer	Calcium	19.0	--	--	--	--	1
	Magnesium	30.0	--	--	--	--	1
	Sodium	431	--	--	--	--	1
	Bicarbonate	1,270	--	--	--	--	1
	Chloride	47.0	--	--	--	--	1
	Total dissolved solids	1,150	--	--	--	--	1
Twin Creek aquifer	pH (standard units)	4.8	5.7	7.4	7.7	8.2	7
	Calcium	913	1,120	5,890	10,900	28,700	7
	Magnesium	139	240	706	1,700	1,720	6
	Sodium	9,790	10,300	39,900	56,500	126,000	7
	Potassium	298	301	574	2,900	4,450	7
	Bicarbonate	134	146	281	415	1,310	7
	Carbonate	12.0	--	--	--	--	1
	Chloride	15,500	15,800	83,000	145,000	183,000	7

Appendix F. Summary statistics for produced-water samples, Bear River Basin, Wyoming.—Continued

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Twin Creek aquifer— Continued	Sulfate	550	640	1,650	4,000	18,000	7
	Total dissolved solids	31,100	31,400	137,000	235,000	329,000	7
Nugget aquifer	pH (standard units)	3.3	6.3	6.9	7.4	8.3	14
	Calcium	406	616	735	1,170	6,560	14
	Magnesium	18.0	62.0	117	157	977	14
	Sodium	4,200	6,240	10,300	16,000	35,600	14
	Potassium	31.0	146	524	700	4,520	9
	Bicarbonate	44.0	168	256	305	366	13
	Chloride	2,600	8,400	17,700	28,900	68,500	14
	Sulfate	428	1,800	2,650	3,900	6,400	14
	Total dissolved solids	14,100	18,900	33,500	45,000	113,000	14
	Iron	48,000	--	72,000	--	740,000	3
Thaynes aquifer	pH (standard units)	6.9	--	7.4	--	7.9	3
	Calcium	656	--	960	--	1,460	3
	Magnesium	122	--	195	--	214	3
	Sodium	12,700	--	15,800	--	28,700	3
	Potassium	686	--	--	--	--	1
	Bicarbonate	122	--	205	--	273	3
	Chloride	18,400	--	24,600	--	40,800	3
	Sulfate	1,130	--	3,800	--	4,150	3
	Total dissolved solids	36,600	--	46,100	--	72,600	3
Woodside confining unit	pH (standard units)	8.1	--	--	--	--	1
	Calcium	1,110	--	--	--	--	1
	Magnesium	184	--	--	--	--	1
	Sodium	8,550	--	--	--	--	1
	Potassium	535	--	--	--	--	1
	Bicarbonate	305	--	--	--	--	1
	Chloride	16,100	--	--	--	--	1
	Sulfate	765	--	--	--	--	1
	Total dissolved solids	25,000	--	--	--	--	1
Wells aquifer	pH (standard units)	7.1	--	--	--	--	1
	Calcium	9,900	--	--	--	--	1
	Magnesium	2,700	--	--	--	--	1
	Sodium	40,900	--	--	--	--	1
	Potassium	548	--	--	--	--	1
	Bicarbonate	2,680	--	--	--	--	1
	Chloride	86,000	--	--	--	--	1
	Sulfate	1,800	--	--	--	--	1
	Total dissolved solids	144,000	--	--	--	--	1

Appendix F. Summary statistics for produced-water samples, Bear River Basin, Wyoming.—Continued

[--, not applicable; <, less than; Values in black are in milligrams per liter unless otherwise noted; values in blue are in micrograms per liter]

Hydrogeologic unit	Constituent	Minimum	25th percentile	Median	75th percentile	Maximum	Sample size
Madison aquifer	pH (standard units)	6.1	6.6	7.4	8.3	8.8	8
	Calcium	50.0	318	1,400	4,190	10,700	8
	Magnesium	15.0	37.0	262	635	4,170	8
	Sodium	29.0	2,800	7,400	14,300	44,100	8
	Potassium	8.0	174	600	1,150	1,960	8
	Bicarbonate	39.0	146	482	1,510	5,190	8
	Carbonate	12.0	--	--	--	154	2
	Chloride	82.0	4,000	16,000	26,400	98,000	8
	Sulfate	56.0	124	655	2,190	3,600	8
	Total dissolved solids	327	9,560	29,700	47,400	160,000	8
Bighorn aquifer	pH (standard units)	7.1	--	--	--	8.9	2
	Calcium	632	--	--	--	865	2
	Magnesium	180	--	--	--	306	2
	Sodium	4,430	--	--	--	4,710	2
	Potassium	565	--	--	--	2,270	2
	Bicarbonate	159	--	--	--	1,140	2
	Carbonate	72.0	--	--	--	--	1
	Chloride	8,150	--	--	--	11,100	2
	Sulfate	65.0	--	--	--	--	1
	Total dissolved solids	14,500	--	--	--	19,000	2

Appendix G

*Major-Ion Composition
and TDS-Concentration for
Environmental Groundwater
Samples*

A. Quaternary alluvial aquifers

B. Quaternary terrace-deposit aquifers

C. Quaternary landslide deposits

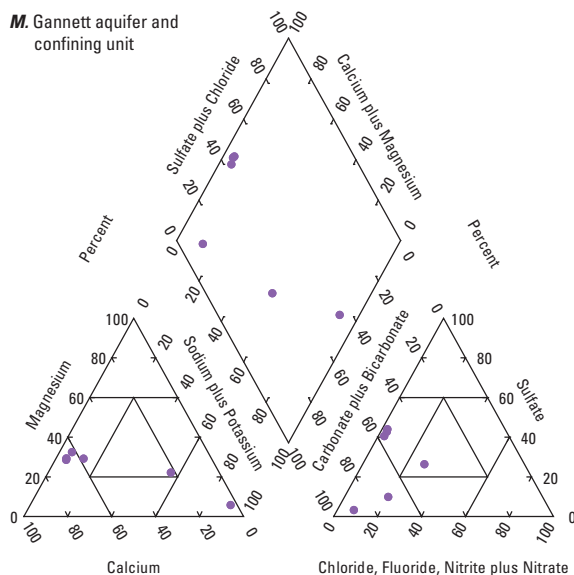**D.** Fowkes aquifer

EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)
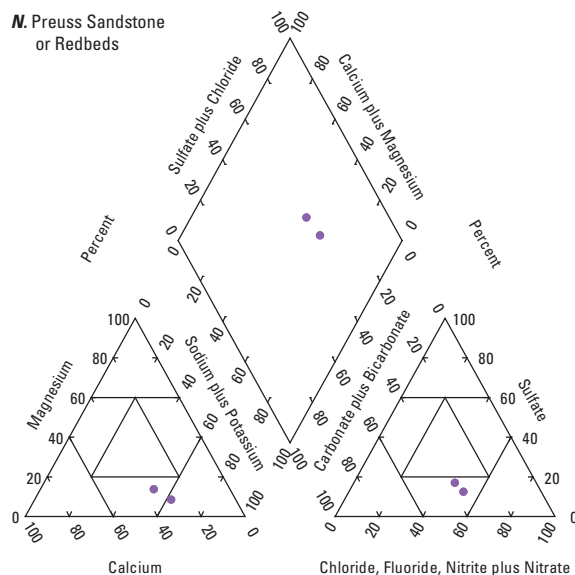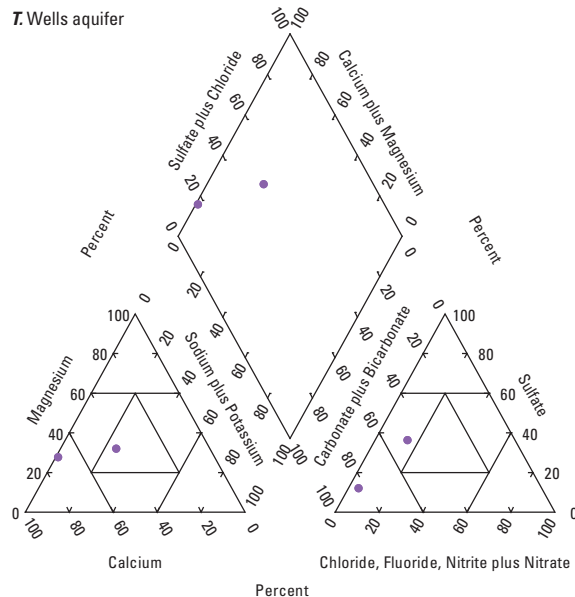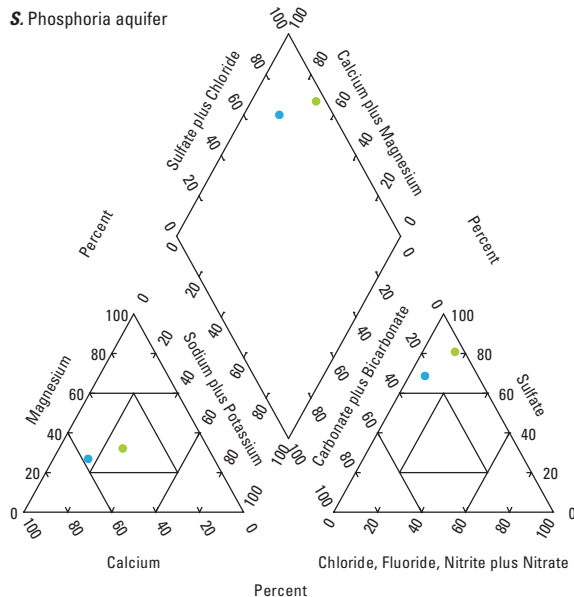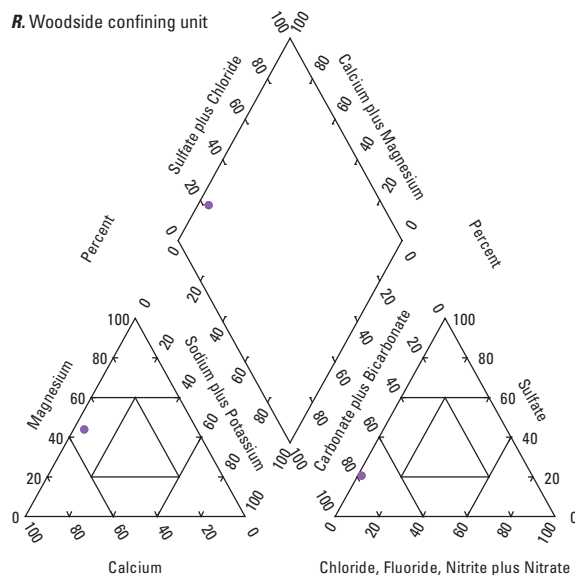
- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples, Bear River Basin.

E. Angelo Member of Green River Formation
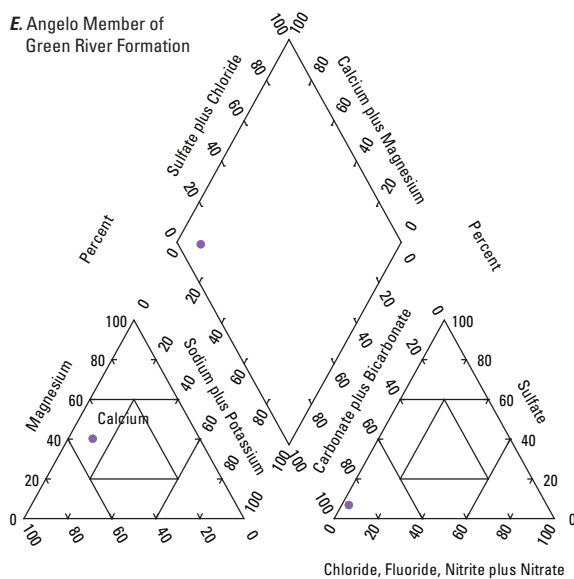
F. Fossil Butte Member of Green River Formation
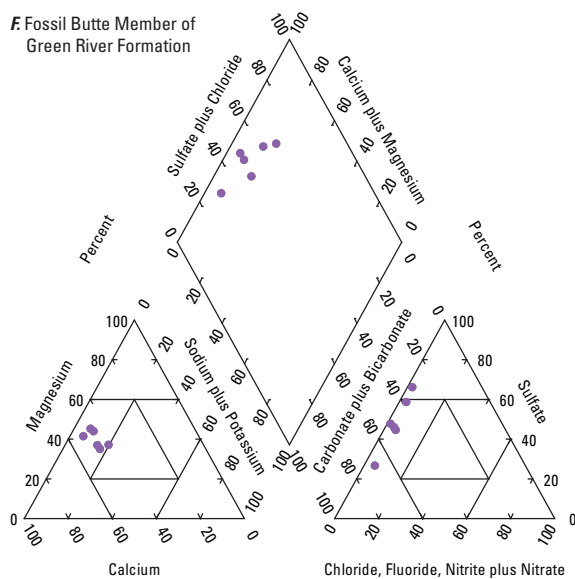
G. Wasatch aquifer
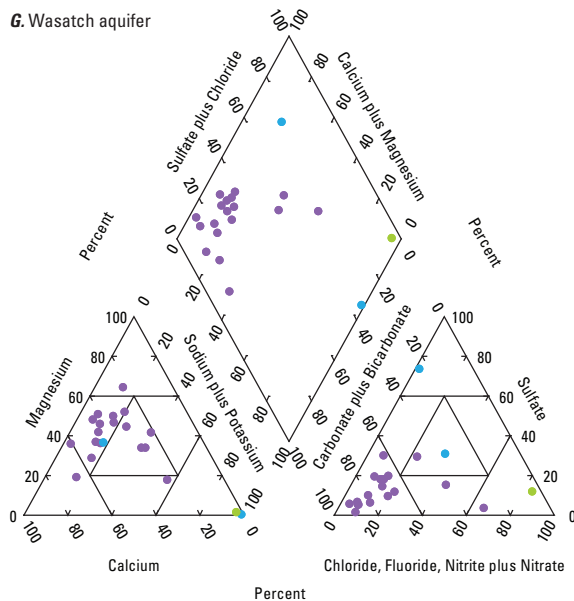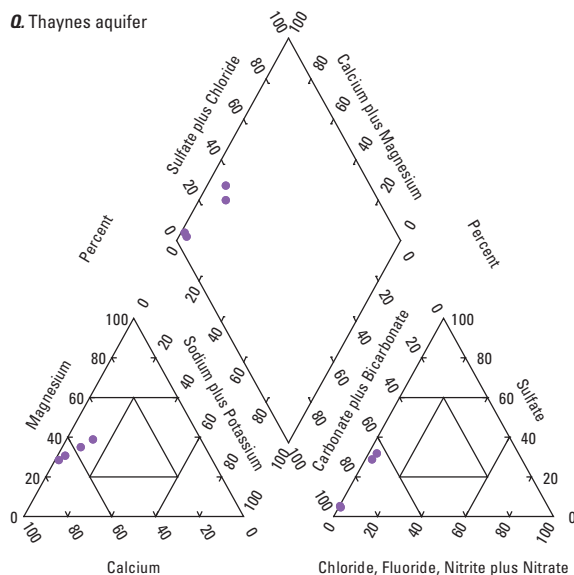
H. Evanston aquifer
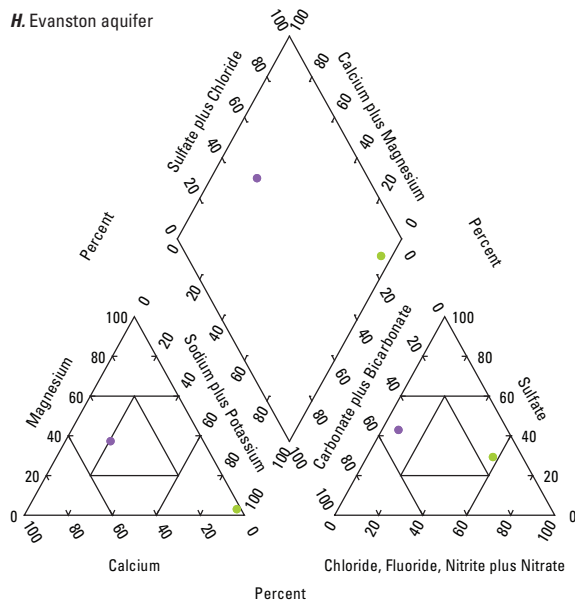
EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)
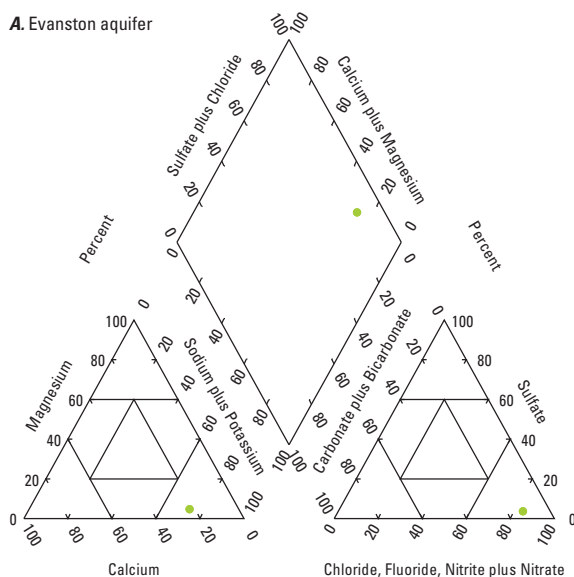
- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples, Bear River Basin.—Continued

I. Frontier aquifer
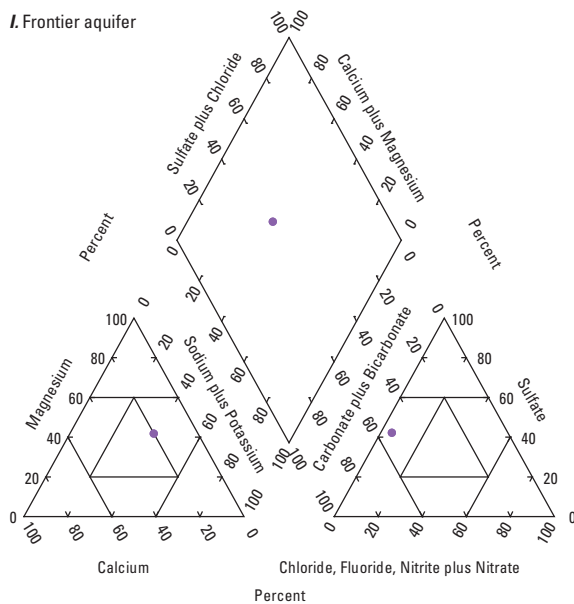
J. Sage Junction Formation
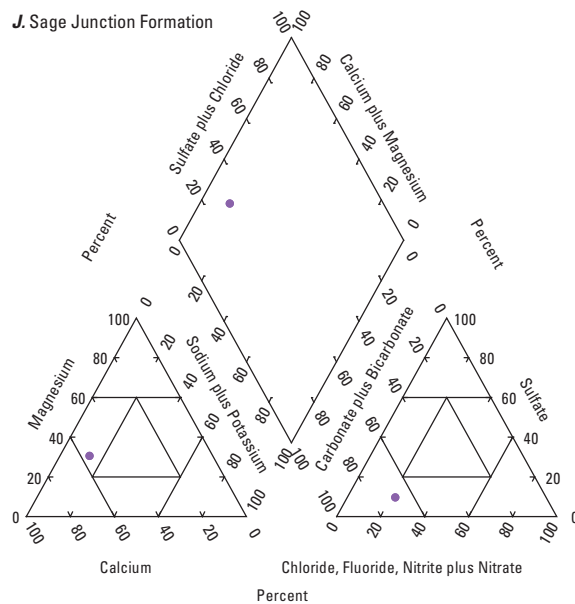
K. Bear River aquifer
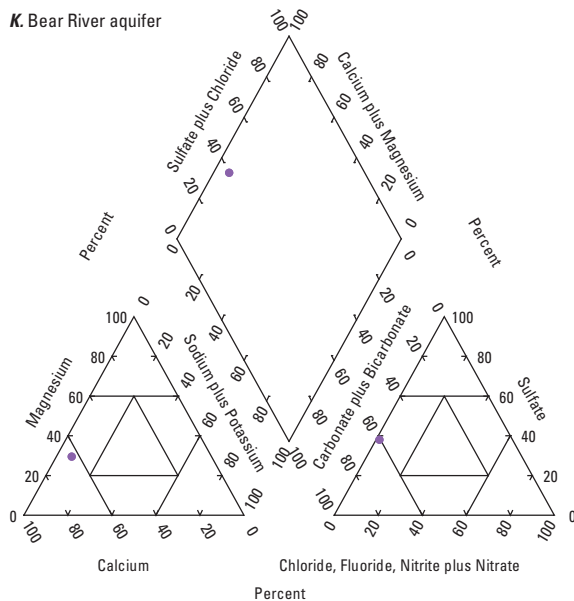
L. Thomas Fork aquifer
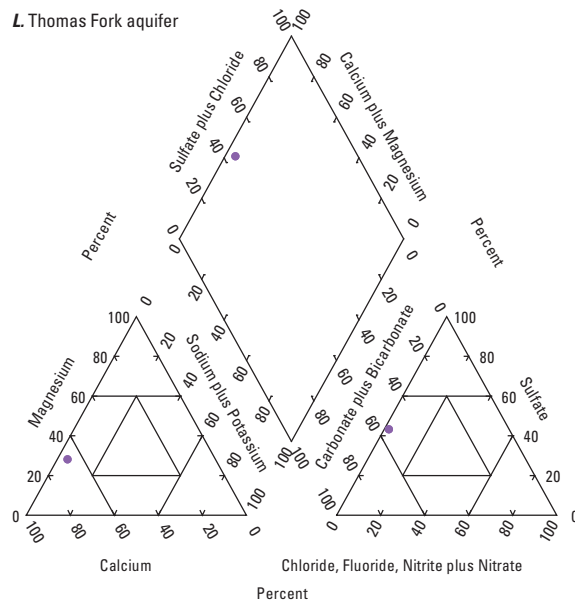
EXPLANATION

**Total dissolved-solids concentration, in milligrams per liter, and
U.S. Geological Survey salinity classification (Heath, 1983)**

● Less than or equal to 999; fresh
● 1,000–2,999; slightly saline
● 3,000–9,999; moderately saline
● 10,000–34,999; very saline
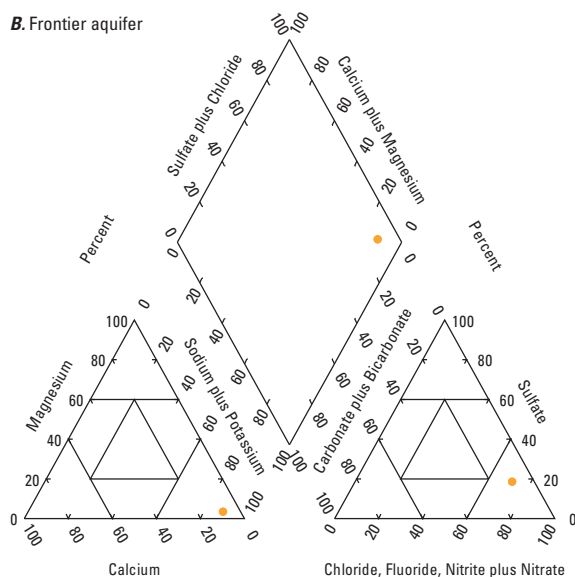● Greater than or equal to 35,000; briny

Appendix G. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples, Bear River Basin.—Continued

M. Gannett aquifer and confining unit

N. Preuss Sandstone or Redbeds

O. Twin Creek aquifer
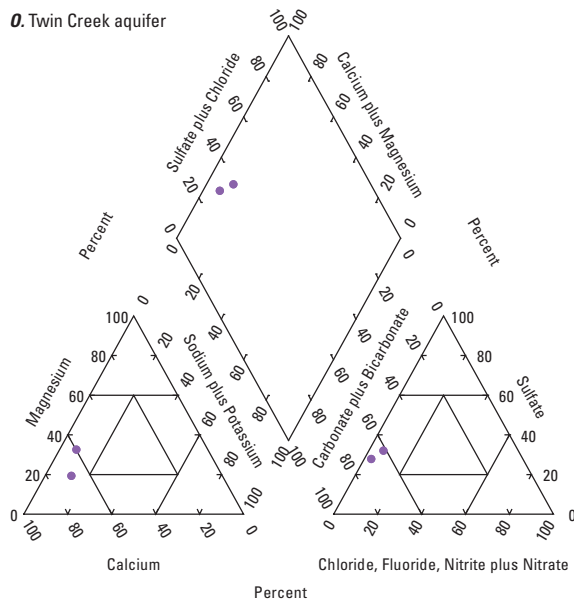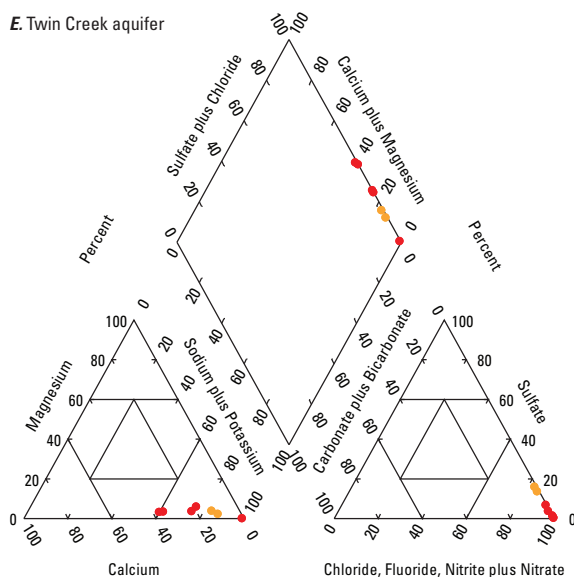
P. Nugget aquifer
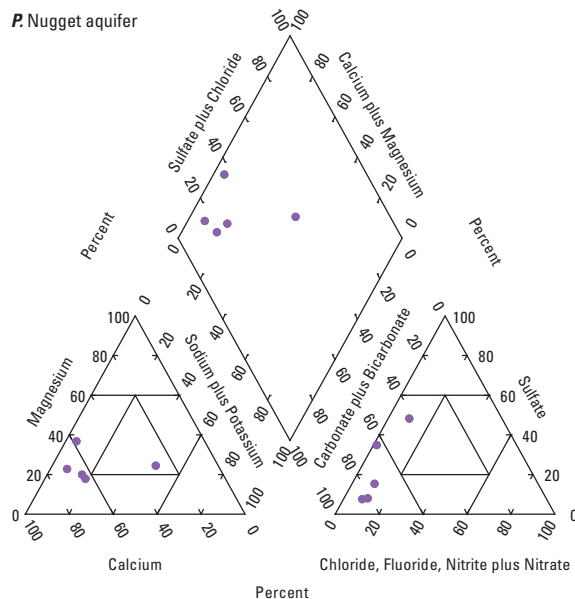
EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples, Bear River Basin.—Continued

Q. Thaynes aquifer

R. Woodside confining unit

S. Phosphoria aquifer

T. Wells aquifer

EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)
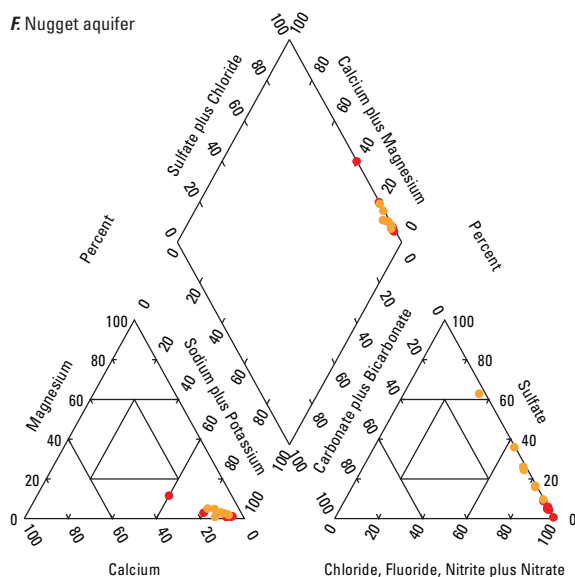
- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix G. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for environmental groundwater samples, Bear River Basin.—Continued

Appendix H

*Major-Ion Composition
and TDS-Concentration
for Produced Groundwater
Samples*

A. Evanston aquifer

B. Frontier aquifer

C. Aspen confining unit
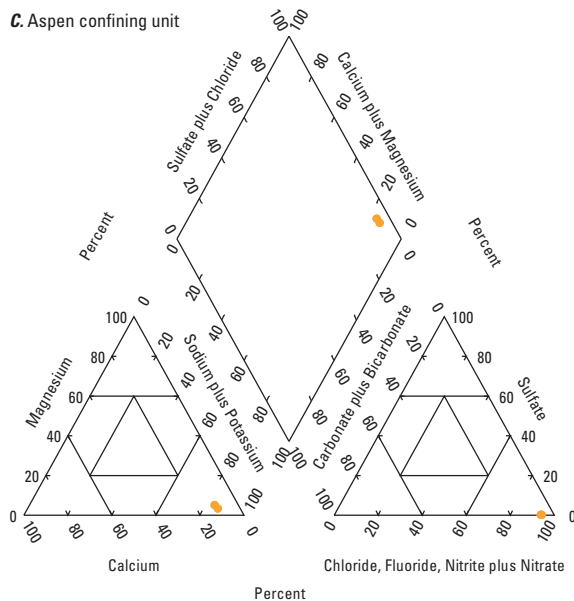
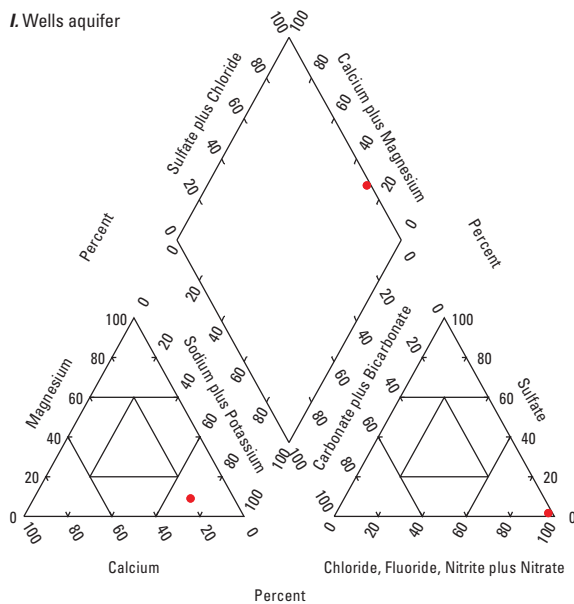**D.** Bear River aquifer
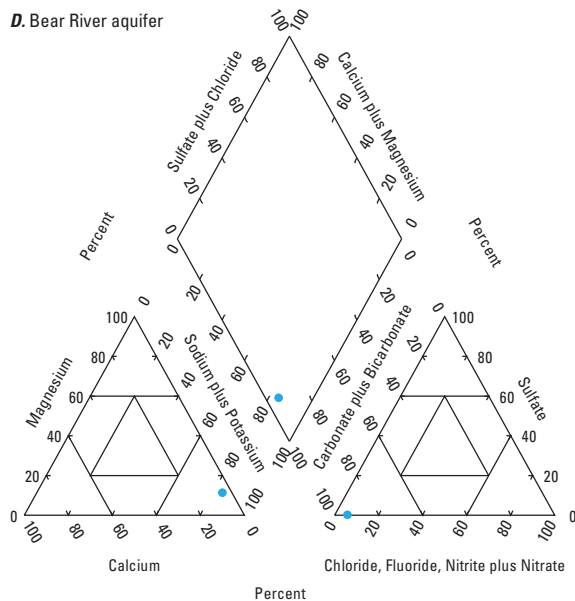
EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- ● Less than or equal to 999; fresh
- ● 1,000–2,999; slightly saline
- ● 3,000–9,999; moderately saline
- ● 10,000–34,999; very saline
- ● Greater than or equal to 35,000; briny

Appendix H. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced groundwater samples, Bear River Basin.

E. Twin Creek aquifer

F. Nugget aquifer

G. Thaynes aquifer
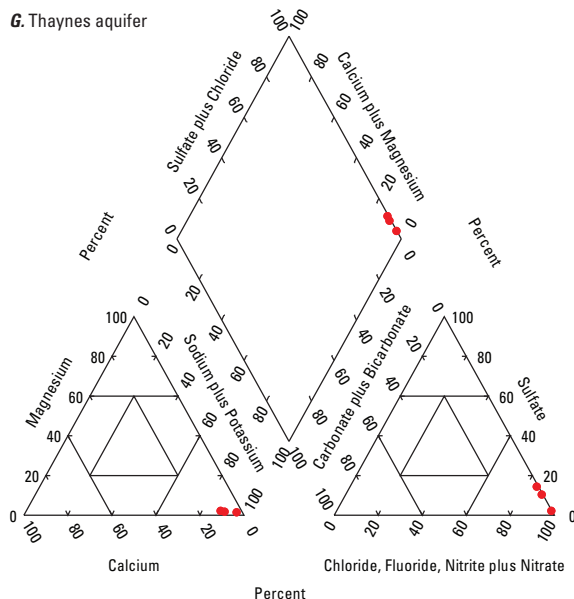
H. Woodside confining unit
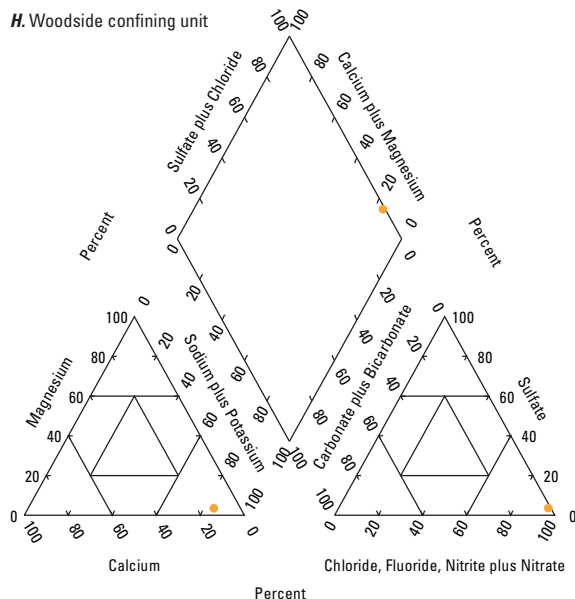
EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)
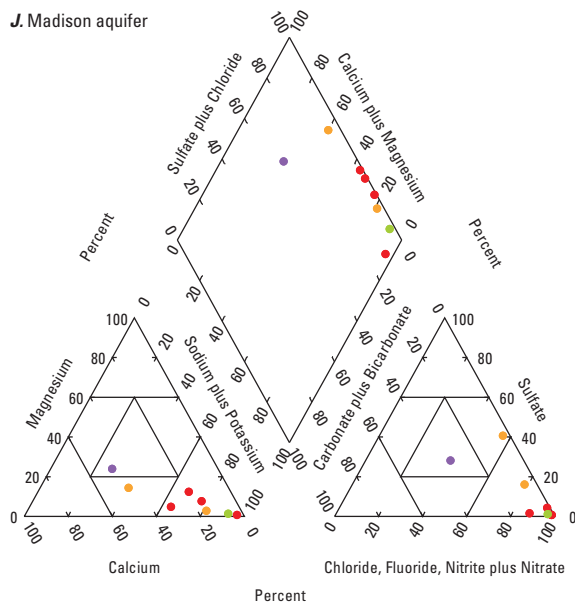
- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix H. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced groundwater samples, Bear River Basin.—Continued
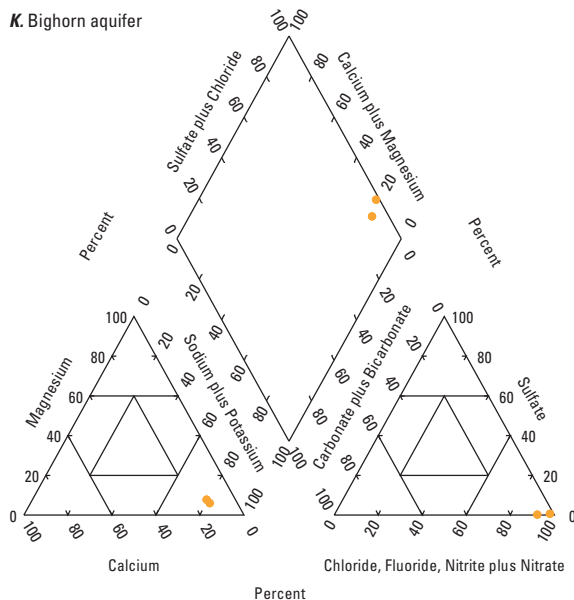
I. Wells aquifer

J. Madison aquifer

K. Bighorn aquifer

EXPLANATION

Total dissolved-solids concentration, in milligrams per liter, and U.S. Geological Survey salinity classification (Heath, 1983)

- Less than or equal to 999; fresh
- 1,000–2,999; slightly saline
- 3,000–9,999; moderately saline
- 10,000–34,999; very saline
- Greater than or equal to 35,000; briny

Appendix H. Trilinear diagrams showing major-ion composition and total dissolved-solids concentrations for produced groundwater samples, Bear River Basin.—Continued

Geology - Interpreting the past – providing for the future